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Short communication

Stream zoobenthos under extreme conditions in the high Andean plateau of Argentina (South America)

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ABSTRACT

The Puna de Atacama plateau (South America; altitude 3800 m)—with its endorheic basins and containing one of the principal deposits of lithium worldwide—is one of the most extensive tablelands on the planet. Information on the invertebrates of those internal catchment areas, however, is scarce and fragmentary. We describe here for the first time the structure and composition of the invertebrate assemblage of the Olaroz Salar (Argentina), analyze the spatial-temporal changes, and examine the relationships between the organisms and their environment. Samplings of the sediment and aquatic vegetation were carried out in three affluent streams of the salar during the wet season and the limnologic variables were measured in situ. Of the 26 taxa collected, the most highly represented were Nematoda, Harpacticoida, *Paranais litoralis*, and *Limnocythere* sp.; while *Heterocypris incongruens* registered the highest abundance. The total density was correlated with the sediment organic matter and differed among the streams. The abundance, richness, and diversity decreased upon proximity to the salar. The invertebrate assemblage varied spatially, with the conductivity gradient being one of the principal conditions influencing the distribution. Redundancy-detrended analysis demonstrated that within these environments the conductivity, amount of organic matter, and vegetation were the principal determinants of benthic development. The insularity, fragility, and low resilience of these wetlands necessitate adequate administration policies for their long-term management and utilization, particularly in view of the growing demand for mineral exploitation in the region.

1. Introduction

Although most of the rainfall over land is drained to the oceans, some water bodies are located in closed hydrologic systems—endorheic watersheds—where the topography prevents access to the seas (Demergasso et al., 2003; Reutter et al., 2006). The inland water flows into those arid basins, where evaporation occurs, leaving a high concentration of minerals and other products of erosion from the input water flow. In South America these dry lakes are referred to as salars. Their surface is typically dry, hard, and rough during the dry season, but wet and very soft in the rainy period, usually encrusted with precipitated salts. Since the main drainage systems of these temporary water bodies are primarily produced through evaporation and seepage, salars are generally more sensitive to the input of environmental pollutants and therefore more vulnerable to contamination than water bodies that have access to oceans (Gajardo et al., 2006). Salars are of limnological interest due to their insularity, specialized fauna and many endemic species (Moreno et al., 2010; Scheihing et al., 2010). Moreover, these systems exhibit a high fragility and low resilience to anthropogenic influences (Locascio de Mitrovich et al., 2005). However, to date, ecological information on them is still scarce.

As human development has expanded into previously uninhabited desert areas, many of these river systems have been altered (Gajardo et al., 2006; Wolfram et al., 1999), e.g. for mining. The Andean salt-lake sediments are very rich in lithium, and 49% of the world's lithium reserves are present there (Alonso, 2006; Gruber et al., 2011). Because of the increasing demand for lithium-based rechargeable batteries used in electronic products and hybrid motor vehicles, these ecosystems are attracting an increasing economic interest. In view of their high vulnerability to anthropic impact, these salars are in need of careful attention and responsible management. Therefore, the objectives of the present study were:

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a) to conduct for the first time a characterization of the habitats in the three streams feeding the Salar de Olaroz, through a description of the structure and composition of the benthic communities; b) to analyze the spatial–temporal changes in the invertebrate assemblages; and c) to examine the relationship between the environmental conditions and the zoobenthos distribution, identifying which variables may be influential or causal.

2. Sampling design, data collection and statistic analysis

The Puna de Atacama is a high-altitude plain in western-central South America and one of the most extensive high plateaus in the world. Its altitude is ca. 3800 m (Alonso, 2006; Demergasso et al., 2003; Márquez-García et al., 2009), and is one of the driest regions on the entire planet. The climate is dry and cold with average temperatures that fluctuate daily to a greater extent (up to 30 °C) than the seasonal variation. The rainfall shows a high degree of seasonality (200 mm–800 mm) with a rainy period (November–April) and a dry one (June–October). The vegetation consists of scattered grasses, low shrubs, and thorny species such as the cactus pad. In the higher-altitude areas the vegetation is sparse, adapted to radiation, dryness, severe cold, and winds (Cabrera and Willink, 1973). The salars therein are considered to be the remnants of the extensive lakes that once occupied the high plains. The Salar de Olaroz is fed by three meandrous streams: Rosario, Esquina Cerro Overo, and Archibarca. In the alluvial valley of Rosario Stream vegetation is scarce, while the terrain's perimeter has a xerophilous-type flora. Neither floating nor submerged aquatic vegetation is present, so the arrival of light and the radiation levels are maximal. The Esquina Cerro Overo Stream has ferruginous sediments; its floodplain contains grassy vegetation with little development of aquatic and riparian plants. The Archibarca Stream has soft, greenish sediments along with the greatest vegetation cover which at some sites spreads over the entire channel. The floodplain consists of a low-lying ground vegetation cover characteristic of saline soils.

The study area was located in a hardly accessible region characterized by a pronounced seasonal climate, so during the wet period two samplings were performed (December 2009 and April 2010) at six sites located in the three streams: Esquina Cerro Overo (S1–S2; upstream-downstream, respectively); Archibarca (S3–S4, upstream-downstream); and Rosario (S5–S6, upstream-downstream). The samples were removed with an Ekman grab (100 cm^2, triplicate per site) in combination with a sieve (500 μm pore size) for the collection of organisms on the vegetation, and fixed in situ (5% v/v formaldehyde). The percent vegetation cover and perimetral vegetation were estimated from a mapping of the site, performing transects in a stretch of 50 m (Cortelezzi et al., 2013; Elosegui and Sabater, 2009). The following limnologic variables were measured: pH, conductivity, temperature, and dissolved-oxygen concentration.

In the laboratory, the samples were washed on a sieve (500 μm pore size) and stained with erythrosin B. The invertebrates were separated and their abundances expressed as ind./m^2. A fraction of the sediment (50 g wet weight) was separated for determination of the percent organic matter by the method of calcination (LOI) (APHA, 1998). For the identification of the organisms we followed Brinkhurst and Marchese (1992), Fernández and Domínguez (2001), Lopretto and Tell (1995), and Merritt et al. (2008).

The benthic community was analyzed on the basis of the average abundance of individuals and the season of the year along with ecologic parameters: Shannon diversity (H'; in Shannon and Wiener, 1963), equitability (J), and taxonomic richness (S; i.e., the number of taxa). To establish the differences existing between these ecologic parameters vs.: (1) the streams under study, (2) the two seasons, and (3) the distance of the sites from the salar, the Kruskal Wallis test ($p < 0.05$; STATISTICA 8.0, StatSoft, Inc., 1984–2007) was used. To analyze the relationship between the percent organic matter and the average abundance of organisms, the Spearman rank correlation (r_s) was employed.

The detrended correspondence analysis (DCA) by segments was applied to determine if the taxa responded linearly to the gradients or passed through an optimum with respect to the environmental variables. Since the maximal length of the resulting gradient was 2.42; a linear response was assumed and the redundancy detrended analysis (RDA) applied in order to explore the relationship between the taxa studied and the environmental variables registered at the sampling sites (Ter Braak and Verdonschot, 1995). The data for the abundance were transformed to ln $(x + 1)$, and all the taxa were included. The physicochemical variables were standardized and included in the analysis, except for the temperature. The inflation values of the data were <7. The statistical significance of all the canonical axes was evaluated by the Monte-Carlo test (499 permutations, reduced model, $p < 0.05$). The first two ordination axes were selected for graphical representation.

3. Results and discussion

The water temperature and the conductivity showed wide variations; in contrast, the variations in the pH and dissolved-oxygen concentration were somewhat narrower, being the pH neutral, slightly tending to alkaline (Table 1). Sites S2, S3, and S5 contained aquatic vegetation represented by *Potamogeton conf. pusillus* and *Salicornia* sp. Their distribution was irregular and coverage varied considerably among the sampling sites. The invertebrates were represented by 26 taxa from 7 phyla. Nematoda, Harpacticoida, the ostracod *Limnocythere* sp., and the oligochaete *Paranais litoralis* were the most highly represented, with each one attaining a frequency of occurrence above 45%. Nematoda and Harpacticoida were registered at all the sites and on every sampling occasion except at S6 during the autumn and at S4 during the spring. Total abundance varied between 366,000 ind./m^2 (S2, in autumn) and

Table 1
Mean and standard deviation values of the physicochemical variables registered at the sampling sites in proximity to the Salar de Olaroz, Jujuy (Argentina). S1 (23°34′54″ S, 66°40′24″ W), and S2 (23°34′35″ S, 66°40′41″ W) were placed at Esquina Cerro Overo Stream; S3 (23°37′23″ S, 66°51′15″ W), and S4 (23°37′34″ S, 66°50′40″ W) at Archibarca Stream; while S5 (23°07′45″ S, 66°39′45″ W), and S6 (23°10′24″S, 66°37′15″ W) at Rosario Stream. Sp (Spring), Au (Autumn), masl = meters above sea level.

Sites	Height (masl)	Width (m)	pH		Conductivity (μs/cm)		Dissolved oxygen (mg/l)		Temperature (°C)	
			Sp	Au	Sp	Au	Sp	Au	Sp	Au
S1	3915	3.1	7.38 (±0.13)	8.05 (±0.39)	2913.3 (±80.5)	3016.7 (±182.1)	5.8 (±0.33)	12.57 (±1.06)	20.53 (±2.57)	13.1 (±0.2)
S2	3913	3.8	8.68 (±0.02)	8.89 (±0.10)	3340 (±206)	4183.3 (±52.5)	5.2 (±0.14)	9.27 (±0.39)	27.33 (±0.46)	7.9 (±0.3)
S3	4033	0.7–4	7.18 (±0.12)	7.80 (±0.05)	2203.3 (±103.3)	1768 (±87.9)	6.52 (±0.10)	12.73 (±1.16)	16.67 (±0.46)	10.7 (±0.1)
S4	4021	0.19	7.99 (±0.03)	8.57 (±0.34)	2030 (±81.6)	2070.7 (±126.8)	6.24 (±0.19)	14.2 (±0.94)	13.30 (±0.16)	5.9 (±0.1)
S5	4009	3.9–4.5	8.48 (±0.04)	8.77 (±0.08)	9543.3 (±395)	5450 (±43.2)	7.35 (±0.25)	16.23 (±1.48)	22.30 (±0.62)	2.5 (±0.3)
S6	3976	5.6	8.47 (±0.01)	8.81 (±0.05)	11643.3 (±449.4)	5353.3 (±804)	7.39 (±0.46)	12.30 (±2.06)	28.53 (±0.25)	7.4 (±0.9)

Table 2
Benthic invertebrates in Salar de Olaroz. Jujuy (Argentina). Total abundance (*N*, ind./m^2) and taxon specific abundances in percentage (%). S1 and S2 were placed at Esquina Cerro Overo Stream; S3 and S4 at Archibarca Stream; while S5 and S6 at Rosario Stream. Sp (Spring), Au (Autumn).

Taxon specific abundance	S1		S2		S3		S4		S5		S6	
Taxa	Sp	Au	Sp	Au	Sp	Au	Sp	Au	Sp	Au	Sp	Au
Turbellaria	–	–	–	–	–	–	–	–	3.16	7.32	1.56	4.76
Rotifera	–	–	–	–	0.23	–	–	–	–	–	–	–
Nematoda	47.03	6.66	17.25	2.30	13.70	25.20	58.29	6.24	7.04	5.85	24.65	–
Oligochaeta												
Paranais litoralis	24.54	37.01	–	6.19	11.61	18.90	–	29.65	–	–	–	–
Tubificinae	–	–	–	–	–	–	–	–	0.51	0.49	–	–
Enchytraeidae	–	0.08	–	–	0.23	0.31	27.14	–	–	–	–	–
Hirudinea	0.15	–	–	–	0.46	0.63	–	0.15	–	–	–	–
Tardigrada	0.53	0.12	–	–	–	–	–	–	–	–	–	–
Acari	2.21	0.12	–	0.04	–	–	–	–	–	–	–	–
Cladocera	–	–	–	–	–	–	–	–	0.20	–	–	–
Harpacticoidea	23.09	0.04	21.18	0.15	1.63	2.20	–	2.97	78.67	19.51	70.36	95.24
Cyclopoidea	0.46	0.08	–	–	11.61	0.31	4.52	–	1.02	–	2.18	–
Ostracoda												
Heterocypris incongruens	1.75	54.63	5.88	91.11	–	–	–	59.61	–	–	–	–
Limnocythere sp.	–	–	50.98	–	3.48	2.83	–	0.97	5.00	5.85	–	–
Amphipoda												
Hyalella sp.	–	–	–	–	20.79	2.36	–	0.11	–	–	–	–
Chironomidae												
Cricotopus sp.	–	–	3.92	–	–	–	6.03	0.30	–	0.98	–	–
Orthocladius sp. 1	–	–	–	–	–	–	–	–	–	–	–	–
Orthocladius sp. 2	–	–	–	–	3.90	–	–	–	–	–	–	–
Polypedilum sp.	–	–	–	–	32.33	46.93	–	–	–	–	–	–
Podonomus sp.	–	–	–	–	–	–	–	–	0.71	–	–	–
Dolichopodidae	–	–	–	–	–	–	4.02	–	2.96	–	1.09	–
Ephydridae	0.15	0.43	0.78	0.18	–	0.31	–	–	0.10	–	–	
Ceratopogonidae	–	0.85	–	–	–	–	–	–	–	57.07	–	–
Syrphidae	0.08	–	–	–	–	–	–	–	–	–	–	–
Psychodidae	–	–	–	0.04	–	–	–	–	–	–	–	–
Elmidae	–	–	–	–	–	–	–	–	0.61	2.93	0.16	–
N	174,933	172,200	17,000	366,000	28,700	42,333	6633	179,400	65,333	13,667	21,367	4200

4200 ind./m^2 (S6, in autumn; Table 2). The content of organic matter ranged between 9.84% (S3, in spring) and 0.73% (S4, in autumn). A positive correlation between the density of organisms and the percent of organic-matter of sediments ($r_s = 0.634$; $p < 0.0001$) was observed. During the autumn, the peaks in density registered at sites S2 and S4 were both owing to the pronounced abundance increment of *Heterocypris incongruens*, reaching values of 333,500 and 107,000 ind./m^2; respectively.

The ecologic indices measured reflected the ambient conditions, the most structured sites were those of the Archibarca Stream (S3 and S4) attaining the highest values of diversity (Fig. 1). The abundance of organisms, the taxonomic richness, and the Shannon diversity generally evidenced diminished values upon proximity to the salar, but this pattern was not so evident with the equitability. The Kruskal–Wallis test demonstrated significant differences with respect to the total abundance among the three streams ($H = 7.249$, $p = 0.026$), the distance of the sites from the salar ($H = 3.786$, $p = 0.05$), but not the seasons of the year ($H = 0.484$, $p = 0.486$). Differences in taxonomic richness were registered in accordance with the distance from the salar ($H = 13.5$, $p = 0.0002$), but not among the streams ($H = 1.81$, $p = 0.404$) or between the seasons of the year ($H = 0.159$, $p = 0.689$). Likewise, the diversity exhibited differences in terms of distance from the salar ($H = 5.784$, $p = 0.016$), but not among the streams ($H = 1.095$, $p = 0.578$) or between seasons ($H = 2.404$, $p = 0.121$). In contrast, none of the comparisons tested exhibited significant differences with respect to the equitability (for all three streams, $p > 0.125$).

The ordination of the taxa in relation to the sites and the environmental variables is shown in Fig. 2. The first two axes of the RDA explained 62.2% of the accumulated variance (axis 1, eigenvalue: 0.33; axis 2, eigenvalue: 0.2). The environmental variables that most closely correlated with axis 1 were: conductivity ($r = -0.619$) and perimetrical vegetation ($r = 0.586$), while with axis 2 were: altitude above sea level ($r = 0.673$), vegetation cover ($r = 0.897$) and pH ($r = -0.688$). S3 was oriented in the upper right quadrant in conjunction with the vegetation cover; S1 was correlated with the organic matter and the perimetrical vegetation; whereas sites S5 and S6 exhibited a strong association with the dissolved-oxygen concentration and the conductivity. The RDA distinguished three types of habitats—those being defined by the vegetation cover, the percent organic matter, the conductivity, and the dissolved-oxygen concentration. The greatest extent of vegetation coverage was associated with an assemblage dominated by Hirudinea, Enchytraeidae, the amphipod *Hyalella* sp. and the chironomid *Polypedilum* sp., while the highest values of percent organic matter corresponded to an assemblage dominated by Nematoda and *P. litoralis*. Finally, in association with the conductivity and the dissolved-oxygen concentration were the Turbellaria, the microcrustaceans, the chironomid *Podonomus* sp. and the coleopteran Elmidae.

This study dealt with a complex benthos undifferentiated between the streambed and the water column and containing certain organisms pertaining to plankton, such as Cladocera and Cyclopoida. This type of community—an admixture of associated planktonic and benthonic elements—has been registered in other Andean environments (Locascio de Mitrovich et al., 2005; Scheihing et al., 2010) and probably results from the strong wind action and the shallow depth of the water bodies. Ostracods are usually major components of these systems, both in abundance and frequency, especially in shallow environments (Locascio de Mitrovich et al., 2005; Márquez-García et al., 2009).

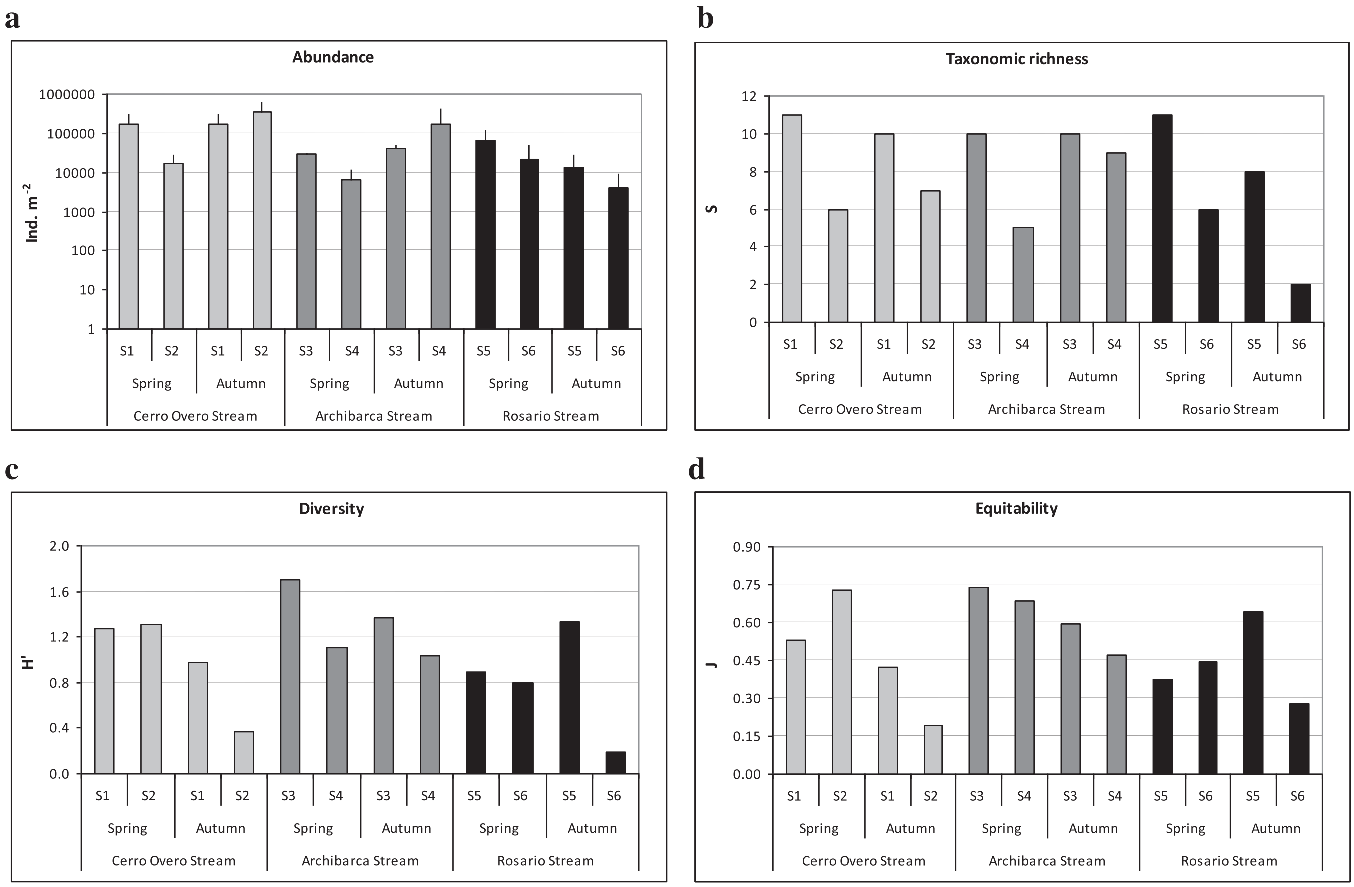

Fig. 1. a) Average total abundance of benthic organisms registered in the Esquina Cerro Overo, Archibarca, and Rosario streams (Jujuy, Argentina) during the study period. Ecologic indices: b) taxonomic richness, c) Shannon diversity, and d) equitability, calculated for the six sampling sites during the two seasons of the year analyzed in this investigation.

Changes in the invertebrate assemblage were associated with alterations on a spatial scale rather than the seasonal climate. We argue that the spatial gradient in conductivity was one of the principal influences conditioning the distribution of the zoobenthos. The decrease in the abundance, taxonomic richness, and diversity was a response to an increase in conductivity when reaching the salar. Conductivity and salinity have been emphasized as key variables influencing the invertebrates in saline lakes, indicating that less saline water offers more favorable conditions for the existence of various taxa (Wolfram et al., 1999). The high conductivity found in the studied streams was mainly due to the presence of dissolved salts such as lithium, borates, and potassium chloride (Orocobre, 2012). This same ecophysiologic relationship had been registered in the Bañado Carilauquen wetland (Scheibler and Ciocco, 2011).

The organic matter percentage and the total vegetation cover were the principal environmental determinants of the development of the benthic community within these extreme environments. The aquatic macrophytes, when present, increased the spatial heterogeneity and provided food, refuge, and breeding sites for the appropriate species, thus reducing the extent of predation and generating an oxygenated environment (Rooke, 1984). Therefore, the development of aquatic vegetation probably favored the formation of habitable refuges in the form of patches that ultimately gave rise to an increase in diversity. The organic matter is also a determining element in the distribution of taxa within the benthos with the nematodes and oligochaetes being strongly associated with that component (Armendáriz et al., 2011).

The conservation of saline aquatic ecosystems has become one of the recent sustainability priorities worldwide. The growing demands for water for mining and the expanding urban centers, coupled with the prospective increase in aridity and reduction in aquatic resources stemming from the currently accelerating global warming, place the dynamics and functionality of those environments at an even greater risk (Márquez-García et al., 2009). Macroinvertebrates have been extensively proposed as one of the groups most appropriate for use as biologic indicators of the ecologic status of wetlands throughout the world (cf. Ocon et al., 2008 and the references therein).

The goal of the present work was to gather the fundamental initial information on the biologic diversity within the tributary streams of the Salar de Olaroz as a prelude to future follow-up investigations aimed at deepening our understanding of the structure and functioning of this ecosystem. Those governmental entities in charge of maintaining the well-being of the environment should be brought to understand the biodiversity and functional organization of these wetlands in order to encourage the implementation of the appropriate action for their administration and proper use over the long term. The preliminary studies carried out here should become a useful tool in view of the frank increase in the worldwide exploitation of mineral beds for potassium, borates, and lithium. Although this research has been focused on a high Andean salar, the authors expect that the information obtained will serve as a

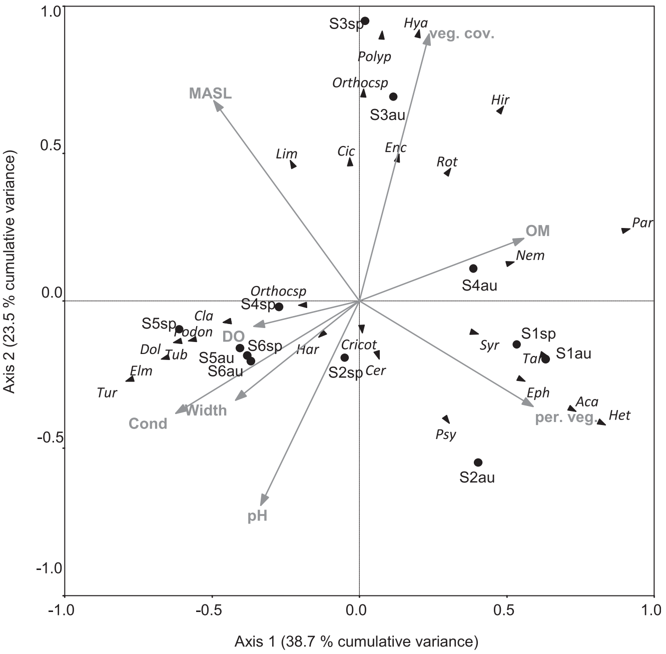

Fig. 2. Triplot of the results from redundancy detrended analysis showing the ordination of the taxa registered and the sampling sites with respect to the environmental variables. Tur: Turbellaria; Rot: Rotifera; Nem: Nematoda; Par: *Paranais litoralis*; Tub: Tubificinae; Enc: Enchytraeidae; Hir: Hirudinea; Tar: Tardigrada; Aca: Acari; Har: Harpacticoidea; Cyc: Cyclopoidea; Het: *Heterocypris incongruens*; Lim: *Limnocythere* sp.; Cla: Cladocera; Hya: *Hyalella* sp.; Cri: *Cricotopus* sp.; Ort1: *Orthocladius* sp.1; Ort2: *Orthocladius* sp.2; Pol: *Polypedilum* sp.; Pod: *Podonomus* sp.; Dol: Dolichopodidae; Eph: Ephydridae; Cer: Ceratopogonidae; Syr: Syrphidae; Psy: Psychodidae; Elm: Elmidae; S1–S6, sampling sites; -au, autumn, -sp, spring; MASL, meters above sea level; per. veg., perimetrical vegetation; veg. cov., vegetation cover; DO, dissolved-oxygen concentration; Cond, conductivity; Temp, temperature; OM, organic matter.

precedent for further studies and mining projects in other regions of the world.

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