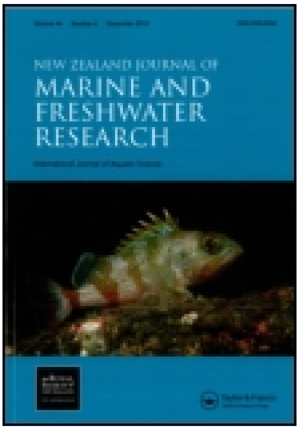

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Relationships between the spatial distribution of oligochaetes (Annelida, Clitellata) and environmental variables in a temperate estuary system of South America (Río de la Plata, Argentina)

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The oligochaete assemblage on the Argentine coast of the Río de la Plata estuary was sampled seasonally within environments having different types of disturbances. Three habitats were sampled: sediments free of vegetation, sediments within bullrush stands and substrates with *Limnoperna fortunei*. The species richness, evenness and Shannon–Wiener diversity values were different among those habitats. The only dominant species (according to the Kownacki index) was *Nais variabilis*. Mean density values varied between 400 and 199,500 ind./m^2. Organic matter, ammonium and phosphates correlated positively with the mean oligochaete abundance, but not with the granulometry. Physicochemical variables and nutrient levels were measured and their relation to the sampling sites assessed through a principal component analysis (41.8% cumulative variance). The canonical correspondence analysis (41.2% cumulative variance) indicated that the oligochaetes distributed along both a eutrophication–pollution gradient and a turbidity–conductivity gradient. These results would be useful for assessing the ecological status of estuaries for a subsequent implementation of appropriate sustainability-management policies.

Keywords: aquatic oligochaete assemblage; large rivers; abiotic affinities; diversity index; dominance; ecological assessment; sustainability

Introduction

The Río de la Plata estuary constitutes an ecosystem of great socio-economic relevance, representing one of the main navigation routes of South America and a major provider of potable water. Since the city of Buenos Aires and extensive suburbs lying along its banks constitute one of the major areas of urban concentration in Argentina, the river is continually subjected to high anthropogenic pressure. This estuary thus suffers from a number of environmental insults, ranging from the input of organic matter and consequent nutrient enrichment resulting from agricultural and cattle-raising enterprises to contamination with waste products from urban and industrial activities. Greater Buenos Aires is a zone where extractive, recreational and port activities coincide with effluxes of industrial and urban wastes and is the location of natural reservoirs and ecological threatened habitats that must be protected for the conservation of biodiversity (Canevari et al. 1999). Nevertheless, despite these ecologically urgent considerations, the information necessary for directing the sustainable management of the river's biotic resources is still lacking (Gómez & Rodrigues Capítulo 2000), and only in recent times have the

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authorities begun to establish the appropriate policies for that evaluation.

The macroinvertebrates in the Río de la Plata River have been studied by a number of authors (Darrigran et al. 1998; Darrigran & López Armengol 1998; Rodrigues Capítulo et al. 1998, 2004; César et al. 2000; Cortelezzi et al. 2007), while the species composition and ecological requirements of oligochaetes in particular have been analysed during recent years in other larger rivers in South America (Montanholi-Martins & Takeda 1999; Takeda 1999; Ezcurra de Drago et al. 2004; Marchese et al. 2005). Furthermore, in various parts of the world, studies on the oligochaete fauna from temperate estuaries subjected to anthropogenic impact have indicated that the most significant environmental factors affecting their distribution are the salinity, turbidity, discharge, trophic condition, sediment characteristics and general quality of the bodies of water in question (Moroz 1994; Finogenova 1996; González-Oreja & Saiz-Salinas 1999; Seys et al. 1999).

In contrast, little is known about the oligochaete species of the estuary system of the Río de la Plata; nor have these annelids yet been placed under intensive scrutinisation despite their prominent presence within the river's invertebrate fauna and their potential usefulness as indicator organisms to assess the state of well-being of the aquatic ecosystem. The objective of this investigation was, therefore, to describe the composition and spatial distribution of the aquatic oligochaetes in the Argentine freshwater tidal zone of the Río de la Plata with an aim of establishing key background information on them that can eventually serve to evaluate the ecological state of the river for future use in the establishment of sustainability-monitoring practices.

Material and methods

Study site

The Río de la Plata estuary receives all the water from the river's extensive basin of about 3.1 million square kilometres—encompassing territories within Argentina, Bolivia, Brazil, Paraguay and Uruguay—and especially from the Paraná and Uruguay rivers, its major tributaries (OAS 1971). The river is 320 km long and 220 km wide at its mouth on the Atlantic Ocean; its total surface has been estimated at 30,000 km^2 and its flow at 23,000 m^3/s. After Boschi (1988), the river is divided into three sections according to the depth and degree of marine influence on the water salinity: the upper section—extending down to the imaginary line joining Punta Lara (Argentina) at 34°50′S, 57°53′W and Colonia (Uruguay) at 34°28′S, 57°51′W—is characterised by shallow waters (2–5 m) with very low salinity (0.3); the middle section—between Punta Piedras (Argentina) at 35°27′S, 56°45′W and Montevideo (Uruguay) at 34°55′S, 56°13′W—is of depths between 6 and 7 m and salinities between 0.3 to 5; and the outer section—between Punta Rasa (Argentina) at 36°22′S, 56°46′W and Punta del Este (Uruguay) at 34°58′S, 54°56′W—has a depth ranging from 6 to 16 m and salinities from 5 to 25.

In addition to hydrophytes, the Argentine coast of the Río de la Plata is dominated by two types of natural substrates: soft substrata, formed by fine sand, silt and clay, and hard substrata formed over a mantle of caliche that can outcrop throughout certain areas forming a littoral cord (Urien 1967; Boschi 1988; Darrigran & López Armengol 1998).

Sampling of oligochaetes

Seasonal samplings were performed in winter and spring 2005, and in autumn and winter 2006 at 11 sites along the Argentine coast of the Río de la Plata estuary, located between 34°29′S, 58°28′W (at the mouth of the Luján River) and 35°16′S, 57°13′W (the cape Punta Indio), thus covering a stretch of approximately 220 km of shoreline (Fig. 1). This section of the estuary system corresponds to the geomorphologic unit known as Franja Costera Sur and is a freshwater zone (conductivity values

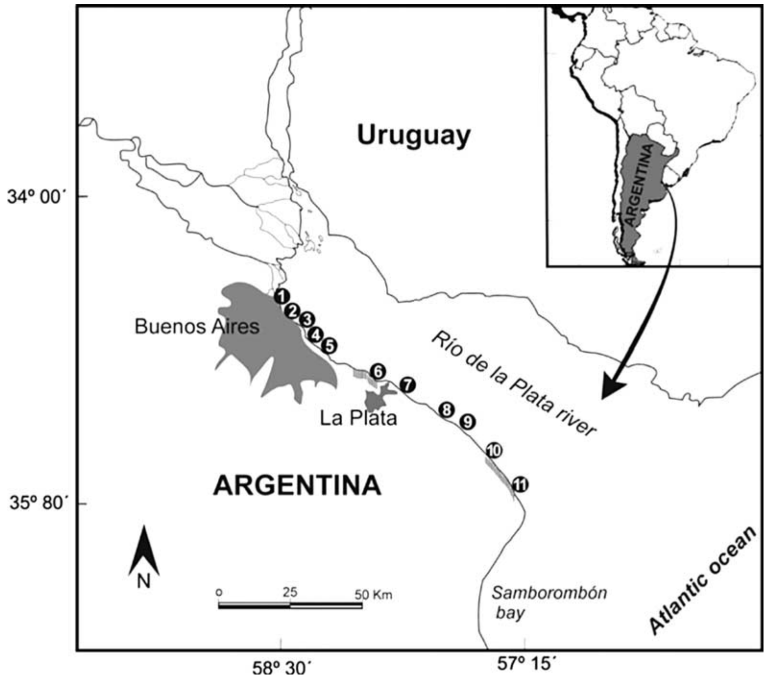

Figure 1 Map of the Río de la Plata estuary system showing the sampling sites. S1, the mouth of the Luján river; S2, San Isidro; S3, the airport of the city of Buenos Aires; S4, Santo Domingo; S5, Berazategui; S6, Boca Cerrada; S7, Punta Lara; S8, Bagliardi; S9, Balandra; S10, Atalaya; S11, Punta Indio. In grey: large urban areas; striped: protected natural areas.

<5000 μS/cm), though subjected to the influence of the Atlantic Ocean tides. The following littoral environments with different types of ecologic disturbances (after Gómez et al. 2009) were selected: Sites 1, 2 and 3, corresponding to highly urbanised areas with navigational and port activities as well as receiving domestic and industrial effluent discharges; Site 4, constituting a highly impacted area where industrial-effluent discharges predominate; Site 5 in close proximity to the sewage discharge of Buenos Aires city; Sites 6 and 7, protected and recreational areas, respectively, but influenced by poor water quality from human activities upstream; Site 8, located close to other major sewage discharges; and Sites 9, 10 and 11, consisting in areas only slightly impacted (thus considered here as 'reference sites')—where Site 11, for its part, is the closest to the maximum turbidity front. Site 4 was sampled only during the first two seasons because of coastal alterations stemming from urban development. All sampling was undertaken within the intertidal zone.

At each sampling opportunity, three replicates (Ekman grab, 100 cm^2) were taken of sediments free of vegetation (sfv) and of sediments within stands of the bullrush *Scirpus californicus* (C.A. Meyer) Steud. (swb). When present, substrates with settlements of the invasive mussel *Limnoperna fortunei* (Dunker, 1857) (sLf) were taken manually covering an area similar to that of the grab. Samples were fixed in the field with 5% (v/v) formaldehyde. For the estimation of organic matter, samples from the first centimetres of the sediment were taken with a core (area 3 cm^2). The turbidity plus the temperature, pH, conductivity and dissolved-oxygen levels were recorded *in situ* with a Turbidity meter 800-ESD and a Horiba

Water Quality Checker U-10, respectively. Water samples were also collected for nutrient analysis (NO_3^-, NO_2^-, NH_4^+ and soluble reactive phosphorous, PO_4^{3-}) as well as for biochemical and chemical oxygen demand (BOD_5 and COD).

In the laboratory, the granulometry analysis was carried out and classified according to the categories proposed by Folk (1974): clay ($\leq 3.9\,\mu m$), silt (3.9–62.5 μm) and sand ($> 62.5\,\mu m$). Organic matter, expressed as ash-free dry weight, was measured as the difference in weight between the dried mass at 60°C for 48 h and combusted mass at 550°C for 4 h (APHA 1998).

The benthic samples were washed on a 250-μm mesh sieve and stained with erythrosin B. The oligochaetes were sorted from the rest of the zoobenthos under a stereoscopic microscope and classified under a compound microscope according to Brinkhurst & Marchese (1992), Erséus & Gustavson (2002), Opinion 2167 ICZN (2007) and Glasby & Timm (2008). The Enchytraeidae were determined only to the family level since the appropriate keys are not available. Oligochaetes were subsequently preserved in 70% (v/v) aqueous ethanol.

Data analysis

A two-way analysis of variance (ANOVA) test was performed to evaluate the fluctuations in each environmental variable recorded: the seasonal variation was analysed using the sampling dates as multiple input data and the spatial variation using the sampling sites as multiple input data.

The oligochaete assemblage was evaluated on the basis of the diversity index (Shannon & Wiener 1963), the evenness and the species richness. To analyse the differences registered at each sampling site among the three types of habitats sampled (the sfv, swb and sLf) one-way ANOVA tests were performed. The dominance index of Kownacki (1971) was also calculated and applied.

Pearson's correlation coefficient was used to analyse the relationships between: (1) the nutrient concentration vs the oligochaete total abundance, (2) the percentage organic matter vs the oligochaete mean density, and (3) each of the sediment particle sizes considered in this study vs the oligochaete mean density.

Two-way ANOVA test was performed to analyse the seasonal and spatial variations of the oligochaete total densities [$\log_e (x+1)$].

Where statistically significant differences were found in the ANOVA tests performed, subsequent Student–Newman–Keuls tests were applied (Underwood 2007).

The relationship between the sampling sites and the standardised physicochemical variables measured was explored through the principal component analysis (PCA). The detrended correspondence analysis (DCA) by segments was used in the biotic data to determine if the species responded linearly to gradients or passed through some environmental optimum. Since the maximum gradient length in standard deviation units obtained in this analysis was 3.45, we assumed a unimodal response model for the species. We therefore decided to use a canonical correspondence analysis (CCA) to explore the relationship between the oligochaete abundance and the environmental variables recorded at the sampling sites (ter Braak & Verdonschot 1995). The species abundances were $\log_e(x+1)$-transformed and all taxa included except inmature forms of *Limnodrilus* spp (referred to as *Tin*; cf. Table 1). The physicochemical variables were standardised. Their variance-inflation factors were found to be <4. The COD and NO_2^- were excluded because their test for significance had failed ($P = 0.124$ and $P = 0.656$, respectively; ter Braak & Verdonschot 1995). The significance of all canonical axes was evaluated through the Monte Carlo test (499 permutations under the reduced model, $P < 0.05$). The first two axes of the ordination were selected for graphical representation.

Table 1 List of oligochaete species collected at the sampling sites in the Río de la Plata estuary (Argentina), with the abbreviation of each species and the dominance-index category defined according to Kownacki: dominant (10–100), subdominant (1–9.99), adominant A (0.1–0.99) and adominant B (0–0.099).

Species	Abbreviation	Dominance value
Clitellata Naididae		
Limnodrilus hoffmeisteri Claparède, 1862	Lh	5.404
Limnodrilus udekemianus Claparède, 1862	Lu	0.199
Limnodrilus claparedianus Ratzel, 1868	Lc	0.109
Aulodrilus pigueti Kowalewski, 1914	Aup	0.026
Tubificinae inmature without hair chaeta	Tin	2.787
Nais variabilis Piguet, 1906	Nv	19.261
Nais communis Piguet, 1906	Nc	1.921
Nais bretscheri Michaelsen, 1899	Nbr	0.152
Pristina macrochaeta Stephenson, 1931	Pm	0.363
Pristina leidyi Smith, 1896	Pl	0.378
Pristina aequiseta Bourne, 1891	Pa	0.203
Pristina biserrata Chen, 1940	Pb	0.001
Pristina longidentata Harman, 1965	Plg	0.449
Pristina jenkinae (Stephenson, 1931)	Pj	0.255
Pristina osborni (Walton, 1906)	Po	0.136
Pristina proboscidea Beddard, 1896	Pp	0.012
Pristina longisoma Harman, 1977	Plm	0.013
Pristina breviseta Bourne, 1891	Pbr	0.013
Pristina notopora Cernosvitov, 1937	Pn	0.027
Stephensoniana trivandrana (Aiyer, 1926)	St	0.393
Stylaria lacustris Lamarck, 1816	Sl	0.101
Dero sawayai Marcus, 1943	Ds	0.208
Dero obtusa d'Udekem, 1885	Do	0.0002
Dero (Aulophorus) furcatus (Müller, 1773)	Df	0.025
Paranais frici Hrabé, 1941	Pf	5.179
Slavina appendiculata d'Udekem, 1855	Sa	0.182
Slavina isochaeta Cernosvitov, 1939	Si	0.156
Chaetogaster diastrophus (Gruithuisen, 1828)	Cds	2.733
Chaetogaster diaphanus (Gruithuisen, 1828)	Cdp	0.128
Amphichaeta leydigi Tauber, 1879	Al	0.022
Allonais paraguayensis (Michaelsen, 1905)	Ap	0.001
Enchytraeidae	ENCH	2.856
Narapa bonettoi Righi y Varela, 1983	Nb	0.003
Opistocystidae	OPIS	0.002
Megadrili	MEGA	0.686
Polychaeta Aphanoneura *Aeolosoma* sp.	Ae	0.335

Results

Physical and chemical quality of the water

Many physicochemical variables recorded exhibit major fluctuations over the area studied, a characteristic in keeping with estuarial environments. Table 2 gives the mean values and their ranges. The ANOVA tests performed to evaluate the seasonal variation showed statistically significant differences in temperature ($P < 0.001$), dissolved-oxygen levels ($P = 0.004$), COD ($P = 0.006$) and BOD_5 ($P = 0.032$). The water temperature exhibited a seasonal pattern

Table 2 Mean values of physicochemical variables measured at the sampled sites in the Río de la Plata estuary (Argentina); minimum and maximum values are indicated between brackets.

Sampling Sites	Temp. (°C)	Turbidity (NTU)	pH	Cond. (μS cm^{-1})	NO_3 (mg l^{-1})	NO_2 (mg l^{-1})	NH_4 (mg l^{-1})	PO_4 (mg l^{-1})	D.O. (mg l^{-1})	BOD (mg l^{-1})	COD (mg l^{-1})
Site 1	20.5	48.27	7.78	265.5	0.647	0.034	0.279	0. 32	8.61	4.75	15
	(16.6–24)	(19.3–80.6)	(7.2–9)	(232–324)	(0.39–0.88)	(0.03–0.05)	(0.04–0.64)	(0.09–0.93)	(5.25–12)	(1–13)	(4–24)
Site 2	18.35	34.85	7.53	329.25	1.082	0.117	0.567	0.233	7.24	5	11.5
	(12.6–25)	(21.7–65.4)	(7.3–7.7)	(266–419)	(0.82–1.34)	(0.07–0.20)	(0.11–1.37)	(0.16–0.41)	(6.35–8.2)	(1–12)	(4–16)
Site 3	20.12	44.1	7.4	283.75	0. 871	0.069	0.243	0.119	5.99	4	12
	(16.2–28)	(22.6–63.5)	(7.2–7.8)	(195–330)	(0.75–0.94)	(0.05–0.11)	(0.05–0.37)	(0.11–0.13)	(4.95–7.2)	(1–10)	(4–19)
Site 4	21	24.6	7.5	1042	0. 283	0.015	0.294	1.026	4.23	36.5	53.5
	(17–25)	(20.9–28.3)	(7.3–7.7)	(774–1310)	(0.22–0.35)	(0.01–0.02)	(0.06–0.53)	(0.7–1.3)	(0.3–8.16)	(12–61)	(18–89)
Site 5	19.75	30.6	8.53	527	0. 963	0.174	0.558	0.363	10.39	8.25	16.75
	(14.7–26.6)	(15.7–57.3)	(7.9–8.9)	(475–585)	(0.69–1.15)	(0.1–0.26)	(0.22–0.74)	(0.25–0.52)	(8.8–11.75)	(2–13)	(10–23)
Site 6	20.4	46.77	8.28	380	0. 791	0.043	0.193	0.202	9.44	8.75	23.25
	(13.2–31.6)	(42.4–58.3)	(7.4–8.8)	(320–419)	(0.17–1.14)	(0.03–0.06)	(0.03–0.3)	(0.18–0.25)	(8.25–11.7)	(1–15)	(10–31)
Site 7	19.62	40.45	8.48	412.5	0. 925	0.057	0.303	0.426	10.49	9.5	21.5
	(12.3–34)	(20.7–68.3)	(7.9–9.4)	(300–515)	(0.08–1.45)	(0.03–0.08)	(0.03–0.59)	(0.27–0.71)	(7.5–13.2)	(5–14)	(12–28)
Site 8	21	57.22	7.78	606.5	0. 567	0.116	0.585	0.754	7.58	19	47.75
	(13.2–33.6)	(18.5–105.4)	(7.5–8)	(290–907)	(0.18–1.22)	(0.02–0.34)	(0.07–1.13)	(0.3–1.34)	(5.3–10.4)	(11–29)	(16–87)
Site 9	20.67	66.55	8.14	338	0. 381	0.014	0.032	0.145	9.26	8.5	26.5
	(11.7–33)	(47.2–70.7)	(7.3–9)	(196–520)	(0.08–0.86)	(0.001–0.04)	(0.001–0.07)	(0.09–0.21)	(8–12.12)	(6–13)	(18–48)
Site 10	20.77	99.17	7.97	646.5	0. 384	0.015	0.319	0.096	8.7	9	30.25
	(12.5–34)	(50.9–144.8)	(7.4–8.2)	(291–1401)	(0.12–0.63)	(0.004–0.03)	(0.04–1.1)	(0.06–0.15)	(8.4–9.4)	(3–12)	(13–51)
Site 11	18.52	186.52	7.74	2608	0. 331	0. 05	0.252	0.146	9	6.25	41
	(11.2–27)	(172–200)	(7.4–8.2)	(802–4280)	(0.04–0.72)	(0.008–0.16)	(0.02–0.92)	(0.06–0.28)	(7.8–10.1)	(2–11)	(14–71)

typical of temperate climates, ranging between 14.1° and 29.2°C in winter and the end of spring, respectively. Of the spatial variations tested, all environmental variables analysed exhibited statistically significant differences, except for temperature ($P = 0.962$) and NH_4^+ ($P = 0.346$). Moreover, a gradient of turbidity and conductivity were found (Fig. 2a and b): turbidity was the highest in the outer estuary ($P < 0.001$), while the conductivity also increased in the same direction ($P < 0.001$) and was elevated at those sites with industrial or domestic discharges as well (e.g. Sites 4, 5 and 8). Site 4, characterised by low water quality because of industrial effluents, evinced the highest BOD_5 and COD values and the lowest dissolved-oxygen levels (0.3 mg/l). The pH varied between 7.2 and 9.4 both in spring. The lowest NO_3^- values (0.04 mg/l) were registered in autumn at Site 11, while the highest (1.45 mg/l) were recorded in spring, at Site 7; the NO_2^- and PO_4^{3-} levels reached a maximum (0.34 and 1.34 mg/l, respectively) at Site 8, where a major sewage-discharge area is located; the highest NH_4^+ values (1.37 mg/l, Site 2) were registered in a densely populated area.

Oligochaete-assemblage structure

The ANOVA tests performed to analyse differences registered at each sampling site with respect to the diversity index, the species richness and the evenness indicated: (1) statistically significant differences ($P < 0.05$) between sfv and swb for all three parameters; (2) no statistically significant differences ($P > 0.05$) between swb and sLf for all three; and (3) statistically significant differences between sfv and sLf in species richness ($P = 0.001$) and diversity index ($P = 0.006$), but not in evenness ($P > 0.05$). The oligochaete species richness varied between 1 and 21, with the highest values being recorded at the locations closest to major sites of sewage discharge (Sites 5 and 8), as well as in the samples of sediment associated with *L. fortunei* (Fig. 3). Moreover, the diversity varied between 0 (Site 11 in autumn 2006) and 2.02 bits/ind (Site 2 in autumn 2006), with relatively similar values over the entire sampling period (Fig. 3). During the winter of 2005, *Limnodrilus hoffmeisteri* was found only at Site 7. The evenness ranged between 0.33 (Site 11 in autumn 2006) and 0.97 (Site 5 in winter 2005), while the largest fluctuations were recorded in autumn 2006.

According to the Kownacki index, the only dominant species in the locations sampled was *Nais variabilis* (Table 1); accompanied by *Paranais frici*, *Chaetogaster diastrophus*, *Nais communis*, *L. hoffmeisteri*, immature tubificinae (without capillary chaetae) and the Enchytraeidae as subdominant taxa. Additionally, a significant number of rare species—such as *Pristina biserrata*, *Dero obtusa*, *Narapa bonettoi* and *Allonais paraguayensis*—were also registered.

Pearson's correlation coefficients showed: (1) a positive relationship between oligochaete total abundance vs NH_4^+ ($r = 0.489$, $P = 0.03$) and PO_4^{3-} ($r = 0.324$, $P = 0.03$) concentrations, whereas no correlations were observed with respect to NO_3^- and NO_2^- concentrations ($P > 0.05$); (2) a positive relationship between oligochaete mean density vs the average percentage organic matter ($r = 0.698$, $P = 0.017$); and (3) no relationship between each of the sediment particle sizes considered and oligochaete mean density ($P > 0.05$). Fig. 4A and B show the variations in mean abundance of oligochaetes in relation to the average percentage organic matter and particle size, respectively.

The ANOVA test performed to analyse the spatial variations in individual densities gave statistically significant differences between the sampling sites ($P < 0.001$). Unfortunately, the subsequent test conducted (Student–Newman–Keuls) did not enable us to identify those stations that might have been generating the differences (Underwood 2007). Moreover, statistically significant differences in the abundance of oligochaetes throughout the seasons sampled were found ($P = 0.044$). The oligochaete mean density (Fig. 5) varied between

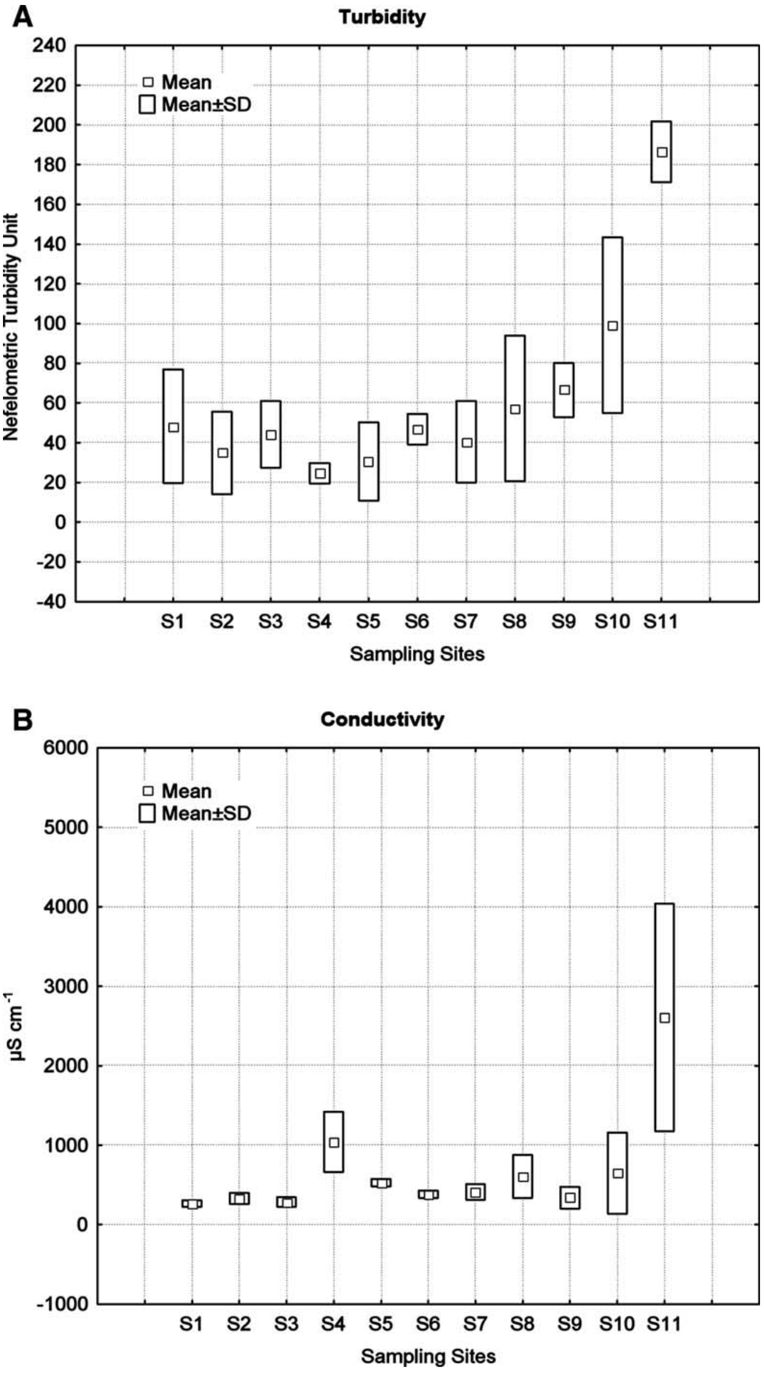

Figure 2 **A** Turbidity and **B** conductivity: mean ± standard deviation values measured over the sampling area.

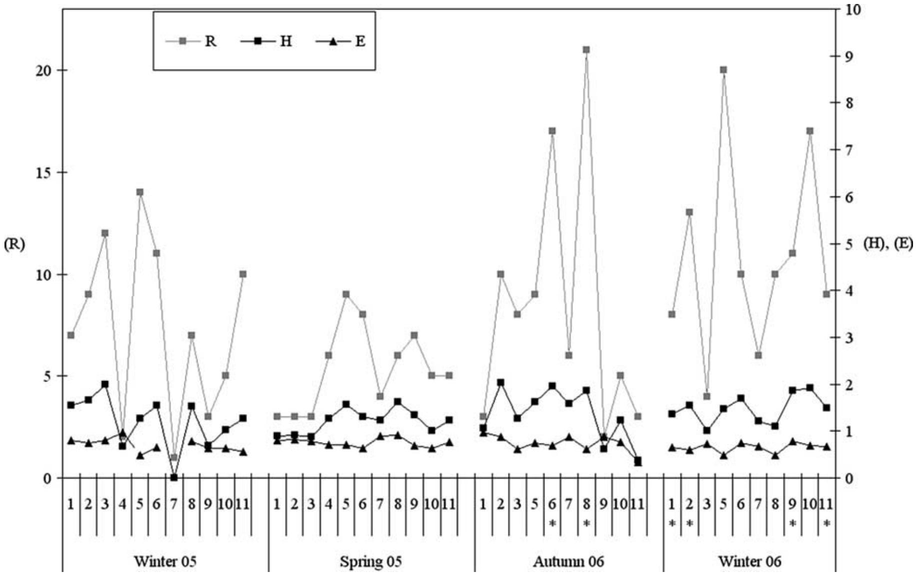

Figure 3 Richness (R), evenness (E) and Shannon–Wiener diversity (H, bits/ind) indices of oligochaetes in the Río de la Plata estuary system during 2005–2006. 1–11: sampling sites. *Samples including settlements of *Limnoperna fortunei*.

400 ind./m^2 (in spring 2005, at Site 3) and 199,500 ind./m^2 (in autumn 2006, at Site 8). At the sampling sites located close to the main sewage discharges of the area (e.g. Sites 5 and 8), the densities of *N. variabilis* (Site 5 in winter 2005) and *C. diastrophus* (Site 8 in autumn 2006) both increased. *Nais variabilis* was furthermore collected at every sampling site and on almost all sampling occasions and its highest densities recorded during winter 2006 in addition to the aforementioned sampling dates. *Paranais frici* was also collected at all stations, but was found in higher abundance during the winter 2006, particularly at the study sites with settlements of *L. fortunei*. *Chaetogaster diastrophus* was registered principally in autumn and spring in the more disturbed localities. *Limnodrilus hoffmeisteri* was registered at almost all sites during winter and spring 2005, whereas its higher densities were recorded in the spring, especially at Sites 6, 8 and 9. Finally, the Enchytraeidae were recorded at all the sampling sites, but in lower numbers than the other species.

According to the PCA results, the first two axes accounted for 41.8% of the cumulative variance of the dataset. The sampling sites were organised along a eutrophication and pollution gradient (axis 1, eigenvalue: 0.219)—particularity at Sites 4, 5 and 8—and also along a turbidity and conductivity gradient (axis 2, eigenvalue: 0.199)—particularly at Sites 9, 10 and 11 (Fig. 6). The first two axes of the CCA accounted for 41.2% of the cumulative variance in the dataset (axis 1, eigenvalue: 0.191; axis 2, eigenvalue: 0.183). Fig. 7 shows the ordination of the oligochaete assemblage with respect to the environmental variables. The variables that best correlated with the CCA axis 1 were: the dissolved-oxygen levels ($r = 0.5504$), the pH ($r = 0.5374$) and NO_3^- ($r = 0.5155$). The variables that best correlated with the CCA axis 2 were: the turbidity ($r = 0.7327$) and the conductivity ($r = 0.4894$). Most species were distributed over a wide range of environmental conditions—e.g. *N. variabilis*, *L. hoffmeisteri*, *P. frici*, *C. diastrophus* and the Enchytraeidae. Especially associated with the

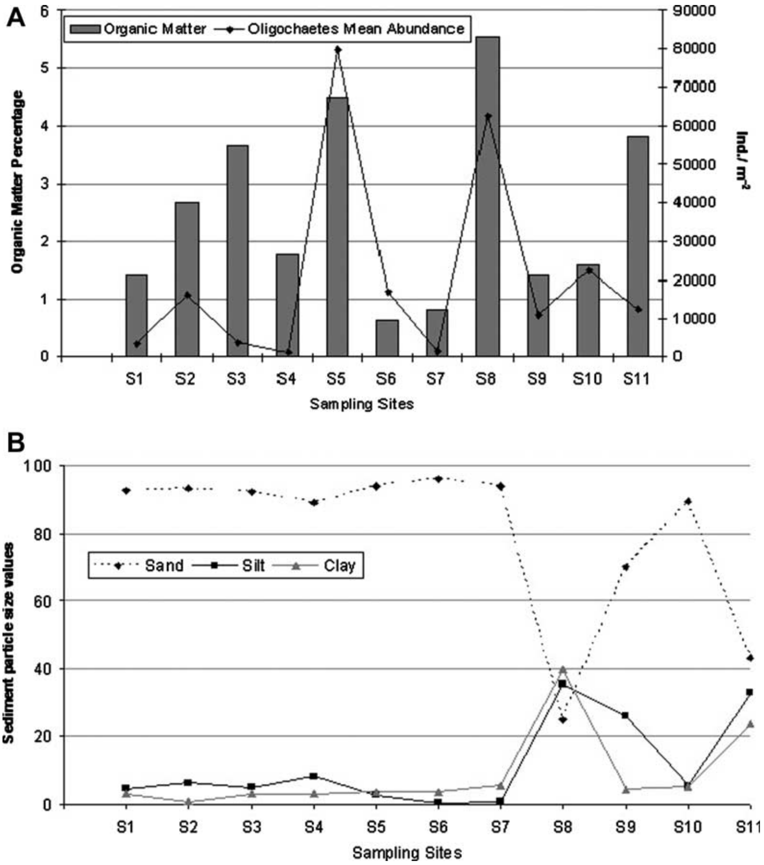

Figure 4 **A,** Relationship between the mean abundance of oligochaetes and the organic matter registered in the sampling sites. **B,** Sediment particle-size values in the sampling localities.

nutrient gradients were *Limnodrilus claparedianus*, *Pristina leidyi*, *Pristina longidentata*, *Stephensoniana trivandrana*, *Dero sawayai* and *Aeolosoma* sp.; *Limnodrilus udekemianus*, *Pristina osborni* and *N. bonettoi* were found in association with the turbidity and conductivity gradients.

Discussion

The study area was between the first two sections of the Río de la Plata estuary (cf. Study site); and even though the area is influenced by ocean tides, that segment of the river is usually classified as continental or freshwater. The continuous changes in the water of the Río de la Plata as a result of tidal flows, saline gradients and the type of sediments present directly affect the distribution of the benthic organisms (Boschi 1988). In the area studied, we found two gradients—one determined by anthropogenic influences related to pollution and eutrophication and the other related to turbidity and conductivity—varying continuously, but reciprocally, over the length of the river; but with the latter gradient being associated mainly with its tidal dynamic as an estuary (also cf. Gómez et al. 2009). From all the variables analysed, the most influential ones in determining the physical and chemical conditions that affected the spatial distribution of the oligochaetes were the turbidity, conductivity, dissolved oxygen, pH and nitrate levels. The abundance of oligochaetes increased together with the ammonium, phosphorus and organic matter. Oligochaete populations respond to changes in the trophic state of the environment, especially when the latter is mainly related to an increase in the deposition of organic matter. Thus, as the conditions deteriorate to reduce the majority of the benthic invertebrates, the abundance of the oligochaetes—especially those that are tolerant to organic pollution, such as *N. variabilis* and *L. hoffmeisteri*—correspondingly increases (Moroz 1994; Finogenova 1996).

The oligochaete assemblages on the banks of the Río de la Plata estuary had been previously studied on the Island Martín García (within the upper section of the river) and on Bagliardi Beach (within the middle section), this last example in association with the invasive mussel *L. fortunei* (Darrigran et al. 1998; Armendáriz & César 2001). As in this study, *N. variabilis*, *C. diastrophus*, *L. hoffmeisteri* and the Enchytraeidae had been the dominant species. The species richness, diversity and evenness values were similar to those registered on other occasions along the coast of the Río de la Plata (Darrigran et al. 1998; Armendáriz & César 2001). In this study, the highest species richness and diversity values could be related to the increased habitat heterogeneity caused by the development of bullrushes and settlements of *L. fortunei*, with these areas manifesting

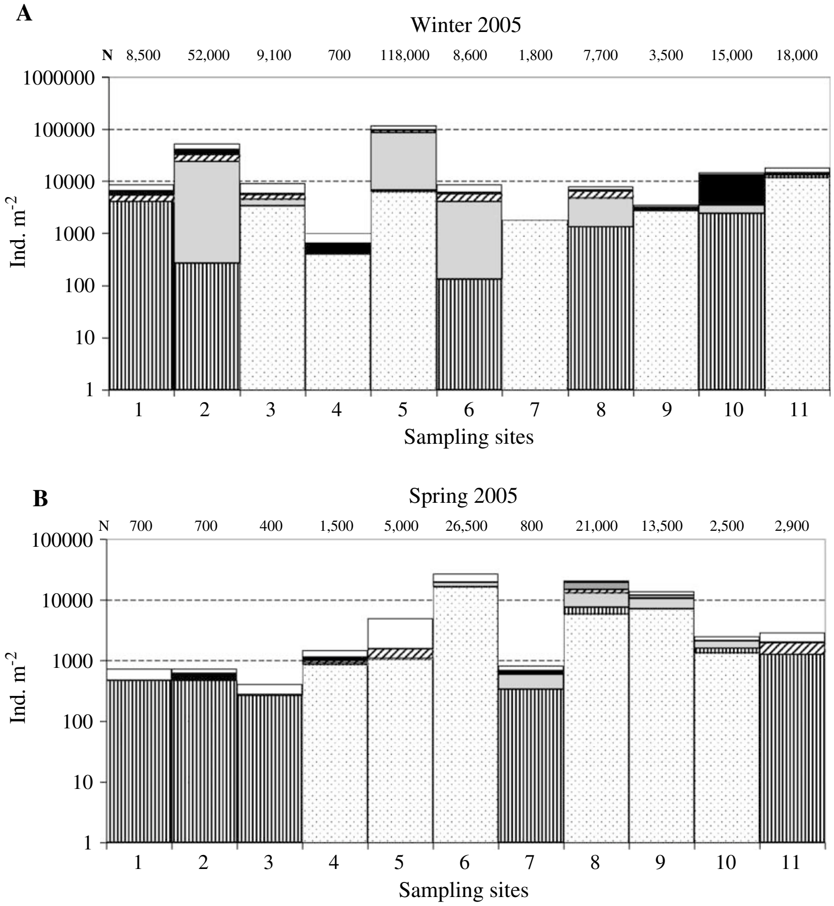

Figure 5. (*Continued*)

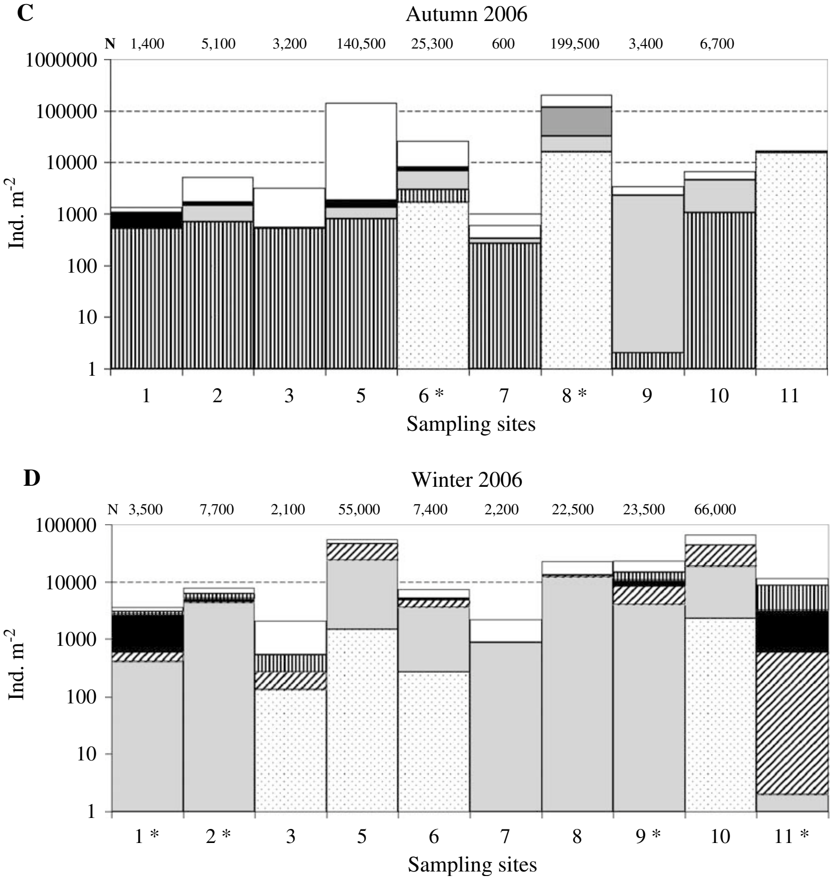

Figure 5 Seasonal distribution and average abundance (ind./m^2) of oligochaetes in each sampling locality (1–11) along the Río de la Plata coast. *Samples including settlements of *Limnoperna fortunei*. ▓ *Chaetogaster diastrophus*; ▨ *Paranais frici*; ▒ *Nais variabilis*; ░ *Limnodrilus hoffmeisteri*; ▥ Tubificinae inmature; ■ Enchytraeidae; □ Others.

significantly higher richness and diversity than those sites characterised by sfv. By contrast, the evenness was higher only in the vegetated areas. The microenvironment developed by the byssus of this mussel allows the development of species with an affinity for organic matter and that feed on detritus, bacteria and the faeces of the mollusc (Harper et al. 1981a, b; Moroz 1994), as could be the circumstance for the oligochaetes found in this study. Moroz (1994) similarly found the highest oligochaete abundance and species richness among the byssi of the mussel *Dreissena* sp. within the silty sands of shallow areas of the Dnieper-Bug estuary.

The oligochaete fauna of the mesohaline part of the estuary studied here appeared similar in species composition and abundance to those of other estuaries (Moroz 1994; Finogenova 1996; Seys et al. 1999). In this investigation, the higher densities were registered during the periods of asexual reproduction in naidine species (not shown). Among the oligochaetes collected, *L. hoffmeisteri*, *N. variabilis* and *P. frici* were found in the upper and

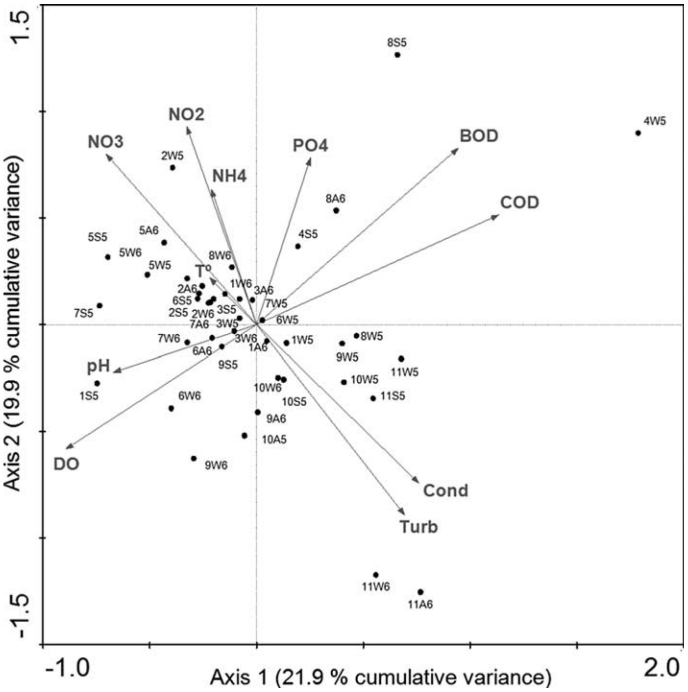

Figure 6 Representation of the first two axes of the principal component analysis (PCA) showing the ordination of the sampling sites with respect to the environmental variables. 1–11, sampling sites; W5, winter 2005; S5, spring 2005; A6, autumn 2006; and W6, winter 2006.

middle section of the estuary, thus demonstrating the high tolerance of these species to both poor conditions of water quality (produced by human activities) and saline stress (from the dynamics of the estuary).

Nais variabilis is frequently found in a large variety of habitats, especially those organically enriched, and often in high densities. The density peaks in the winter of 2005 and in the autumn of 2006 were related to a large population increase in this species (as the result of an intense asexual reproduction; not shown) and in that of another naidid, *C. diastrophus*. Through its feeding habits, *N. variabilis* is seen as a major consumer of the heterotrophic bacteria associated with organic matter in aquatic sediments. Many naidid species are capable of ingesting a high proportion of bacteria, thus acting as significant detritivores in organically polluted aquatic environments; and those species thus represent a key link in the transfer of food energy to upper trophic levels (Harper et al. 1981a, b). The higher densities registered for these two species corresponded to those sites with a particularly high contribution of organic matter because of their proximity to sewage discharges (Sites 5 and 8). Gómez et al. (2009) had studied the community of producers (cyanophytes and diatoms) in the same area of the river and during the same seasons as in this work. What would appear to be cause-and-effect relevance is that the peak in the abundance in the two oligochaete species registered here occurred about 4–5 months after the authors had recorded the peak in cell density of the producers. These occurrences might well be related because the two naidine species belong to the functional feeding group known as the *gatherer-collectors* (Barbour et al. 1999), and the producers could be used by them as a food source. Consistent with the dynamics of this lotic system and with the logic of this putative

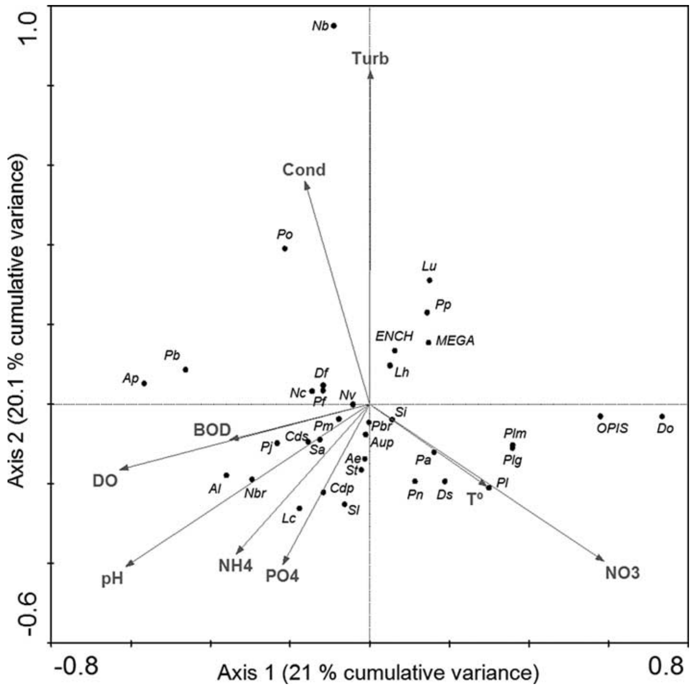

Figure 7 Biplot of the canonical correspondence analysis (CCA) showing the taxa ordination according to the environmental variables. Taxa abbreviations are as in Table 1.

relationship, the peak in abundance of these naidids was recorded some 15 km downstream from the site where Gómez et al. (2009) had cited the maximum cell density of those producers.

Limnodrilus hoffmeisteri is a ubiquitous, eurioic and especially eurihaline species, found very frequently in the basin of the Paraná River, which thrives in thin sediments with abundant organic matter and low dissolved-oxygen levels (Marchese & Drago 1992). The species is usually associated with highly polluted environments (Marchese 1987; Montanholi-Martins & Takeda 1999; Takeda 1999; Ezcurra de Drago et al. 2004; Marchese et al. 2005). Other authors also recorded *L. hoffmeisteri* in the shallow organically enriched sediments of lakes (Casellato & Caneva 1994) as well as in estuaries, in both the freshwater and brackish sectors (Moroz 1994; Finogenova 1996; Seys et al. 1999). In the Río de la Plata estuary, the anthropogenic input of high quantities of nutrients and organic matter (Sites 4, 5 and 8)—the products of industrial and urban sewage discharges—could favour the development and distribution of eutrophic species such as the ones recorded, in addition to *L. udekemianus* and *L. claparedianus* (Moroz 1994; Finogenova 1996; Seys et al. 1999).

Narapa bonettoi is a rheophilic and psammophilic species adapted to environments with both low amounts of organic matter and mobile substrates. This species is frequently found in the main stretch of the Lower Paraguay and Paraná rivers (Paggi et al. 1998; Montanholi-Martins & Takeda 1999; Ezcurra de Drago et al. 2004; Marchese et al. 2005). In the Río de la Plata, this species has been previously recorded in the sandy sediments of the upper section (Armendáriz & César 2001; Cortelezzi et al. 2007). In this study, *N. bonnetoi* was registered in the southern locations (Sites

10 and 11), those considered reference sites (because of their relatively undisturbed environments), although in low numbers.

The oligochaete assemblage of this estuary system is highly complex and capable of responding to local changes in the environmental conditions, thus manifesting the ecological plasticity of many of its species with respect to the existing environmental circumstances. In this way, organisms known to be tolerant (Barbour et al. 1999)—such as *N. variabilis*, *N. communis*, *L. hoffmeisteri* and the Enchytraeidae—were abundant along the river coast, from the more polluted localities (such as Sites 4, 5 and 8) to those considered as reference locations (Sites 9, 10 and 11), although in the latter stations these indicator species were found to be accompanied by others such as *C. diastrophus*, *P. frici* and *S. trivandrana*. As pointed out by Gómez et al. (2009), descriptive investigations on the spatial and seasonal patterns with respect to the composition of environmentally informative species are useful and essential for ecological–manipulative studies. Our intention in characterising the fauna of oligochaetes and identifying their species-specific responses to environmental variables was to enable a more accurate understanding of those influences that determine their composition within this estuary. These results complement previous findings on this question in freshwater environments and could thus be used for constructing approaches to assessing the ecological status of both estuarine ambients in particular and aquatic ecosystems in general. Finally, the results of this study should provide information for the implementation of the appropriate sustainability-management policies with respect to the Río de la Plata estuary and its tributaries.

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