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Assessment of benthic changes during 20 years of monitoring the Mexican Salina Cruz Bay

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Abstract In this work a non-parametric multivariate analysis was used to assess the impact of metals and organic compounds in the macro infaunal component of the mollusks benthic community using surface sediment data from several monitoring programs collected over 20 years in Salina Cruz Bay, Mexico. The data for benthic mollusks community characteristics (richness, abundance and diversity) were linked to multivariate environmental patterns, using the Alternating Conditional Expectations method to correlate the biological measurements of the mollusk community with the physicochemical properties of water and sediments. Mollusks community variation is related to environmental characteristics as well as lead content. Surface deposit feeders are increasing their relative density, while subsurface deposit feeders are decreasing with respect to time, these last are expected to be more related with sediment and more affected then by its quality. However gastropods with predatory carnivore as well as chemosymbiotic deposit feeder bivalves have maintained their relative densities along time.

Keywords Surface sediments · Bay of Salina Cruz Mexico · Mollusk communities · Contamination · Metals · Hydrocarbons

Introduction

The coastal zone receives a large amount of metal pollution from agricultural and industrial activity. Contaminants of major concerns include persistent organic pollutants, nutrients, oils, radio nuclides, heavy metals, pathogens, sediments, litters and debris (Usero et al. 2005).

A number of publications have presented organizing principles by which the fate and effects of broad classes of metals can be understood and predicted in marine systems. These include geochemical considerations (Whitfield and Turner 1987), general biological interactions (Nieboer and Richardson 1980), including bioaccumulation in marine organisms (Fisher 1986) and toxicological effects (Islam and Tanaka 2004).

Alteration of infaunal communities in marine environments receiving petroleum residues has been observed. Field studies of the effects of oil and gas exploration on benthic infauna (considering both drilling mud and associated hydrocarbon burdens) show such trends (Gray et al. 1990; Olsgard and Gray

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1995; Montagna and Harper 1996; Blanchard et al. 2003). Similar patterns also occur at natural marine oil seeps where infauna assemblages exhibit lower diversity and dominance by opportunistic organisms (Steichen et al. 1996).

The aromatic content of petroleum, particularly polycyclic aromatic hydrocarbons (PAH), has been generally assumed to be the principal determinant of the toxicity of oil to aquatic organisms (French 1991; Neff and Stubblefield 1995; Pelletier et al. 1997).

Correlations between sediment composition and the types of communities which occur on the seabed is complicated by the fact that many of the physical properties of the sediments are linked with other factors such as depth of disturbance by wave action, the strength and duration of currents, and interactions with biological components.

Any study designed to evaluate the effect of perturbations on the marine environment is likely to encounter a formidable array of problems. Difficulties may arise from the wide range of physical parameters that have to be considered, or in the interpretation of the sometimes subtle effects on the structure of the ecological community.

Separation of natural fluctuations from changes initiated by the introduction of a chemical disturbance presents a considerable additional challenge. Confounding factors can take many forms such as depth, oxygen levels, salinity and temperature fluctuations, patchiness of food sources, current regimes, and granulometric variations (Saunders and Moore 2004).

Benthic infauna is used extensively as indicators of estuarine environmental status and trends (Pearson and Rosenberg 1978; Dauer 1993; Tapp et al. 1993). Single community attribute measures, including species diversity and abundance, have been suggested to summarize data beyond the level of individual species (Warwick and Clarke 1993, 1994). Pearson and Rosenberg (1978) indicate that benthos respond to pollution stress in stages, with different measures necessary to capture different levels of response.

Another approach is the multi-metric index, which combines multiple measures of community response into a single index, to more effectively capture the different types of response that occur at different levels of stress (Weisberg et al. 1997). Some authors use species composition information directly, usually by describing the assemblage patterns in a comparative multivariate space (Smith et al. 1988).

Warwick and Clarke (1994) showed that multivariate methods of data analysis were more sensitive in detecting differences in community structure between samples in space, or changes over time, in comparison to univariate techniques. The major drawback of the multivariate approach is the necessity to identify all species in samples. However, this can be overcome if lower taxonomic resolution proves to be applicable and sensitive enough to detect changes in macrobenthic communities.

Environmental impacts produced by the cycle of oil exploration and production and their effects in tropical environments at offshore sites in Mexico are not fully documented. The Salina Cruz Bay located at the Ventosa Bay, State of Oaxaca, has undergone considerable development, and consequently urbanization, industrialization. Ship scrapping industry and oil processing in the area has become potential source of contamination to the marine environment.

The present work completes previous reports made on the studied area concerning metal concentrations (Cr, Cu, Fe, Pb, Ni, V, and Zn) in surface sediments (González-Macías et al. 2006), and more recently, total aromatic hydrocarbons and extractable organic matter in the water column and surface sediments (González-Macías et al. 2007).

Several lines of evidence suggested that lead should be considered as a chemical of potential concern and the concentration has constantly increased for the last two decades. Moreover, within sediments, total aromatic hydrocarbons (TAH) concentration (as chrysene equivalents) ranged from 0.01 to 534 $\mu g\ l^{-1}$ in water, and from 0.10 to 2,160 $\mu g\ g^{-1}$ in sediments (González-Macías et al. 2006).

Following our previous work we aims to determine what changes in the benthic community, particularly the mollusks, have occurred in the surface coastal sediments from the inner shelf off Salina Cruz Harbor and coastal areas over 20 years since monitoring began in 1982.

Lying in the second trophic level in the waters' ecosystem, mollusks have long been known to accumulate both essential and non-essential trace elements in aquatic ecosystems (Dallinger and Rainbow 1993). Many researchers have reported the potentiality of using mollusks, as bioindicators or biomarkers for monitoring heavy metal contaminations in aquatic system (Liang et al. 2004; Philips 1980; Bryan et al. 1985; Cossa 1988; Philips and Rainbow 1993;

Andersen et al. 1996; Scanes 1996; Claisse et al. 2001; Szefer et al. 2002; de Astudillo et al. 2002).

Studies on the pollution in Gulf of Paria (de Astudillo et al. 2002), Vienna waters (Gundacker 2000), French coast (Claisse et al. 2001) and Sydney's coastal waters (Andersen et al. 1996) had used biomarkers to monitor the heavy metal pollutions in aquatic systems and the results showed that various degrees of heavy metal pollution existed in mollusks.

As part of a complex food web, infaunal communities are composed of both predators and prey. Trophic level of these species may change during its life cycle as the organism grows and its size, feeding mechanism, and nutritional requirements change during ontogeny.

In the present work, mollusks community characteristics are analyzed base on density, richness and diversity according to Brower and Zar (1977). Nonparametric multivariate analysis of community structure was used in the analysis of benthic community structure.

The data for benthic mollusks community characteristics (richness, abundance and diversity) were linked to multivariate environmental patterns, using the Alternating Conditional Expectations (ACE) method to correlate the biological measurements of the mollusk community with the physicochemical properties and contaminants levels of water and sediments.

In the ACE method two goals are used in regression problems: stabilization of error variance and symmetrization/normalization of error distribution, but a more comprehensive goal is to find those transformations that produce the best fitting additive model. Knowledge of such transformations aids in the interpretation and understanding of the relationship between the response and predictors (Millet and Guelorget 1994).

Methods

Study area

The Salina Cruz Bay, is located at the North side of the Tehuantepec Golf in the Mexican Pacific Ocean (16°06′–16°11′ N and 95°15′–95°07′ W).The study area, 30 km along the coast, includes the Salina Cruz city and harbor. One of the six refineries in the country is located 5 km NE from the harbor with and off-shore outfalls diffuser that discharges the treated sewage effluents to the Bay.

In the outer harbor, three buoys are located for oil exports, and the Salinas de Marques evaporation ponds is placed at 5 km SW of the harbor. The Tehuantepec River discharge to the Bay approximately 1,400 million m^3 $year^{-1}$ of water, while the La Ventosa Estuarine System only discharges water during the rainy seasons, the rest of the year the exchange with the Bay is not constant.

Figure 1 displays a schematic diagram of the study area including the samples locations at La Ventosa Estuary System, and the Tehuantepec River. The main surface current pattern runs east to west. Two seasonal climatic conditions are well defined: rainy from May to September and dry windy seasons from October to April (Chelton et al. 2000).

The area has undergone considerable development since the oil activities began in 1982, and consequently urbanization, industrialization, port areas and

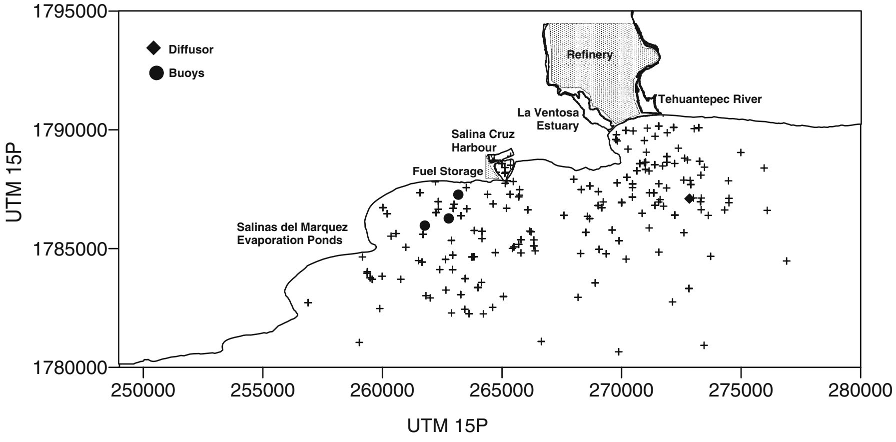


Fig. 1 Map of Salina Cruz Bay and schematic representation of sampling stations

oil production have become potential sources of pollution to the marine environment. A high-energy oceanographic condition prevails in the area that generates dispersal of the different inputs (Trasviña et al. 1995). The main surface current pattern runs east to west.

Sampling

A global positioning system, Micro logic ML-150, was used to locate the sampling sites. Sites and samples were the same used in the work performed for metals, total aromatic hydrocarbons, and extractable organic matter in the water column and sediments (González-Macías et al. 2006, 2007).

A total of 268 sediments samples were collected at 24 sites between October 1982, and September 2002 at different seasons on aboard chartered oceanographic vessels. Most samples of the sediments were collected using a 0.1-m^2 Smith–McIntyre grab in the 5- to 15-cm penetrated layer of sediment, from shallow sites, usually <60 m, in accordance with the bathymetric data of the Bay. The deepest zone is located east to the refinery where the discharge diffuser promotes sediment accumulation in the shallow central zone of the Bay. The samples represent the full range of sediment textures from fine-grained mud to coarse-grained sand.

The location of sites and the number of collected samples for each event at the Bay is shown in Table 1. Total suspended solids in water were measured by calculating the difference between the initial and final weight of a standard glass-fiber filter after filtration (APHA 1995). Sediments grain size was estimated by a combination of wet sieving and pipette analysis (Folk 1974).

Total extractable organic matter was quantified by infrared spectrometry, and the analysis of Cu, Cr, Ni, Pb, V, Fe and Zn was performed by atomic absorption spectrometry (González-Macías et al. 2006) while TAH were evaluated in sub samples of the extracts by fluorescence spectroscopy (González-Macías et al. 2007).

Mollusk sampling and species identification

Each benthic sample was sieved in the field from one half of the sediments collected using the grab through a 0.5-mm screen to remove macro fauna (Gray 1981). Sieved materials were transferred to labeled bottles and preserved in the field using buffered 10% formaldehyde solution. The material obtained from the sample sieving was sorted in the laboratory, separating the organisms according to phylum.

The separated macrofauna from the sediments were preserved in 70% ethanol. As a rule, the organisms were identified to lowest practical taxonomic level, and counted to species level: in a few cases the identification was limited to genus.

The taxonomic identification of the species was obtained using several taxonomic keys among them those of Abbott (1974); Keen (1963, 1971); Keen and Coan (1974); Brusca and Brusca (1990). The geographical distribution and species names were verified in the Discoverlife web site (http://www.discoverlife.org). The mollusk benthic community data was evaluated using density (total number of organisms present per square meter), taxa richness (total number of distinct taxa observed at each station), and Shannon–Wiener diversity index (Warwick and Clarke 1995).

Following Krebs (1989), Species Relative Frequency (RF) defined as the ratio of one species presence to the total frequency of species, and Relative Density (RD) defined as the ratio of species density to the total density of species, were used to obtain the Relative Importance Value (RIV).

$$\mathrm{RIV} = (\mathrm{RF} + \mathrm{RD})/2$$

The benthic mollusks were chose as a suitable taxonomic group to study the impacts of contamination of potential concern. The mollusk species feeding categories were obtained from Stanley (1970).

Bivalves feeding habits in particular surface and subsurface deposit feeders, food sources and strategies have been compared and contrasted by Jumars et al. (1990). Suspension feeders may ingest deposited material and surface deposit feeders may suck in material from the water column (Kamermans 1994).

Concerning gastropods feeding categories, we have limited the analyses to the one feature which can be most easily and reliably assessed: their diets according to the trophic classifications of Hughes (1980), and Britton and Morton (1994). The species list code is shown in Table 2.

Community analysis

Statistical treatment of the data was accomplished by standard statistical software (Statistica 1998) with

Table 1 Sampling period data matrix composition

Date	Season	Geographical limits		Number of samples
		UTM easting	UTM northing	
Oct-1982	Dry/windy	261,570–273,263	1,783,063–1,788,875	24
Dec-1982	Dry/windy	261,570–273,263	1,783,063–1,788,875	23
Apr-1983	Dry/windy	261,570–273,263	1,783,063–1,788,875	24
May-1984	Rainy	253,817–284,524	1,779,753–1,788,806	22
Jul-1988	Rainy	261,699–272,229	1,782,260–1,788,639	24
Sep-1988	Rainy	261,699–272,229	1,782,253–1,788,639	24
Aug-1990	Rainy	259,034–273,727	1,780,656–1,788,092	19
Sep-1997	Rainy	259,363–273,230	1,783,966–1,790,102	16
Dec-1997	Dry/windy	259,363–273,230	1,783,966–1,790,102	18
May-1998	Rainy	269,826–274,472	1,787,133–1,789,954	10
Jun-1998	Rainy	259,363–273,230	1,783,966–1,790,102	18
Aug-2001	Rainy	249,579–273,304	1,779,824–1,790,158	14
Dec-2001	Dry/windy	249,579–273,304	1,779,824–1,790,158	14
May-2002	Rainy	263,999–264,805	1,788,699–1,789,833	6
Sep-2002	Rainy	249,579–273,304	1,779,824–1,790,158	12
Total				268

UTM Universal Transverse Mercator Zone 15P

Surfer-8 software (Surfer 2002) to draw the spatial distribution of the community characteristics.

In order to recognize the temporal trends of community characteristics, the SiZer method described by Chauhuri and Marron (1999) was employed, using the Simple Inference in Exploratory Data Analysis software (Godtliebsen et al. 2003).

The SiZer is a non-parametric method assessing the statistical significance of the reconstructed variation along the time. This inference method appears to be particularly natural and well-suited to temperature and other environmental reconstructions (Holmström and Erästö 2001).

SiZer enables meaningful statistical inference, while doing exploratory data analysis using statistical smoothing methods (e.g. histograms or scatter plot smoothers). A key idea from the SiZer is that useful information is often available from a number of different smooth of the data (i.e. different “levels of resolution”).

The temporal variation can be very large, one might therefore fit a line to the data and make inferences about its slope, in SiZer method instead of considering just a single straight line, point wise are obtained by fitting line locally. The degree of locality is determined by a window on the data and the window size therefore acts as a smoothing parameter that determines how much of the details in the record are smoothed out.

The SiZer colors of the analysis show the decreasing, and the increasing trends that are statistically significant, and those are the only significant structures. The SiZer method also applied to assess the statistical significance of the reconstructed metals variation along the time (González-Macías et al. 2006).

Central tendency analysis of the raw data was performed grouping the variables in three subsets: dry, rainy and global. Differences between those data were detected by means of a “t” Student test for independent samples with different variance (Statistica 1998).

Table 2 Mollusks coding of citations

Feeding categories	
Bivalves	Gastropods
SU: suspension feeder	CP: predatory carnivores
DU: subsurface deposit feeder	CB: browsing carnivores
DS: surface deposit feeder	HO: herbivorous omnivores
DC: chemosymbiotic deposit feeder	HM: herbivores on fine-grained substrates
CAR: microcarnivore	HR: herbivores on rock, rubble or coral substrates
	HP: herbivores on plant or algal substrates
	SU: suspension feeders

First correlation values were investigated using the ACE algorithm of Breiman and Friedman (1985) between paired "independent" predictor and "dependent" response variables. Later multivariate analyses were carried out between the dependent variables with metal and hydrocarbons contents in sediments.

The ACE algorithm is a non-parametric automatic transformation method that produces the maximum multiple correlation of a response and a set of predictor variables. The approach solves the general problem of establishing the linearity assumption required in regression analysis, so that the relationship between response and independent variables can be best described and existence of non-linear relationship can be explored and uncovered. An ACE regression model has the general form:

$$\theta(Y) = \alpha + \sum_{i=1}^{\rho} \phi_i(\mathrm{X}_i) + \varepsilon$$

where θ is a function of the response variable, Y, and ϕ_i are functions of the predictors X_i, i=1,…, p.

Thus the ACE model replaces the problem of estimating a linear function of a p-dimensional variable by estimating p separate one-dimensional functions, ϕ_i, and θ using an iterative method. These transformations are achieved by minimizing the unexplained variance of a linear relationship between the transformed response variable and the sum of transformed predictor variables.

In order to recognize the unique contributions of each independent variable to the prediction of the dependent variable, we compute the partial correlations coefficients, i.e. the correlation between the residuals, after adjusting for all independent variables. The partial correlation represents the unique contribution of the respective independent variable to the prediction of the dependent variable (Cohen and Cohen 1983).

Results

Characterization of the community

Throughout the course of the investigation 461,333 organisms per square meter, belonging to 446 taxa, distributed among 3 classes were found: The bivalves were the most abundant class corresponding to 64% of the density, followed by the gastropods (30%) and finally by the scaphopoda (6%). The 446 taxa, corresponds to 184 genus, 91 families, and 16 super infra order. With regards to the classes; 176 taxa corresponds to bivalves, 248 to gastropods, and 22 taxa to scaphopoda.

Calculated values for characteristics of the community (density, richness and diversity index) with and without extreme values including those for the dry and rainy seasons are shown in Table 3. No seasonal differences between the data subsets were detected by the "t" Student test.

The historical accumulated data portraying the mollusks community characteristics are presented as SiZer plots in Figs. 2, 3, and 4, respectively. The upper part of each graph shows a plot which relates time with mollusks characteristics trends, while the lower part shows the inferred values of the smoothed line (continuous line, secondary Y scale) graphed along the raw data (dotted data, Y left scale).

In each plot, the entire point wise straight lines are shown while the bold lines illustrate the first inference straight line that uses all the data set to perform the time trend inference. Black zones are related with an increase in value, medium gray shows a tendency that is not different from cero, light gray indicates a decreasing value, and white areas indicate that few data are available to do inference. The results suggest that mollusk density seems to increase for the last 6 years of the period frame, while diversity and richness decreases in the same period.

Figure 5 illustrate the spatial distribution of diversity and richness values for the period frame. The results suggest that higher values are found in front of the shallow areas of the Harbor and in front of the area of fuel handling and storage as well as in the marine terminal and delivery buoys.

ACE algorithm was applied forward stepwise to obtain maximal correlations between paired variables using "independent" predictor and "dependent" response variables. Independent predictor variables used were (1) Environmental characteristics (depth; suspended solids in water; MOE in water/sediments), and grain size, (2) Contaminant levels: TAH in water/sediments; Cu; Fe; Ni; Pb; V; Zn and Cr in sediments. Dependent response variables were density, richness and diversity of the mollusks community.

Table 4 shows the results of the calculated percentage explained variance derived from ACE bivariate and multivariate models between community

Table 3 Statistical data for the characteristics of the mollusks community and depth

		Deep (m)	Characteristics of the community		
			Density (org m^2)$^{-1}$	Taxa richness	Diversity index (Shannon–Wiener)
Data with extreme values	Range	3–67	10–47,370	1–46	0.08–3.23
	Mean	18.20	1,828	13	1.94
	SD (# of samples)	7.75(402)	4,095(268)	8.25(227)	0.68(221)
	Variation coefficient (%)	42.58	224.02	61.48	35.26
Global data without extreme values	Range	3–67	10–10,010	1–28	0.08–3.23
	Mean	18.20	1,342	12	1.94
	SD (# of samples)	7.75(402)	1,911(262)	6.94(217)	0.68(221)
	Variation coefficient (%)	42.58	142.32	55.82	35.26
Dry season	Range	3–67	19–10,010	2–28	0.69–3.06
	Mean	19.35	1,784	13	1.88
	SD (# of samples)	8.83(185)	2,467(98)	6.04(99)	0.60(103)
	Variation coefficient (%)	45.64	138.33	46.21	32.11
Rainy season	Range	3–36	10–9,980	1–28	0.08–3.23
	Mean	17.22	1,079	12	1.99
	SD (# of samples)	6.56(217)	1,427(164)	7.61(118)	0.75(118)
	Variation coefficient (%)	38.07	132.26	63.85	37.42

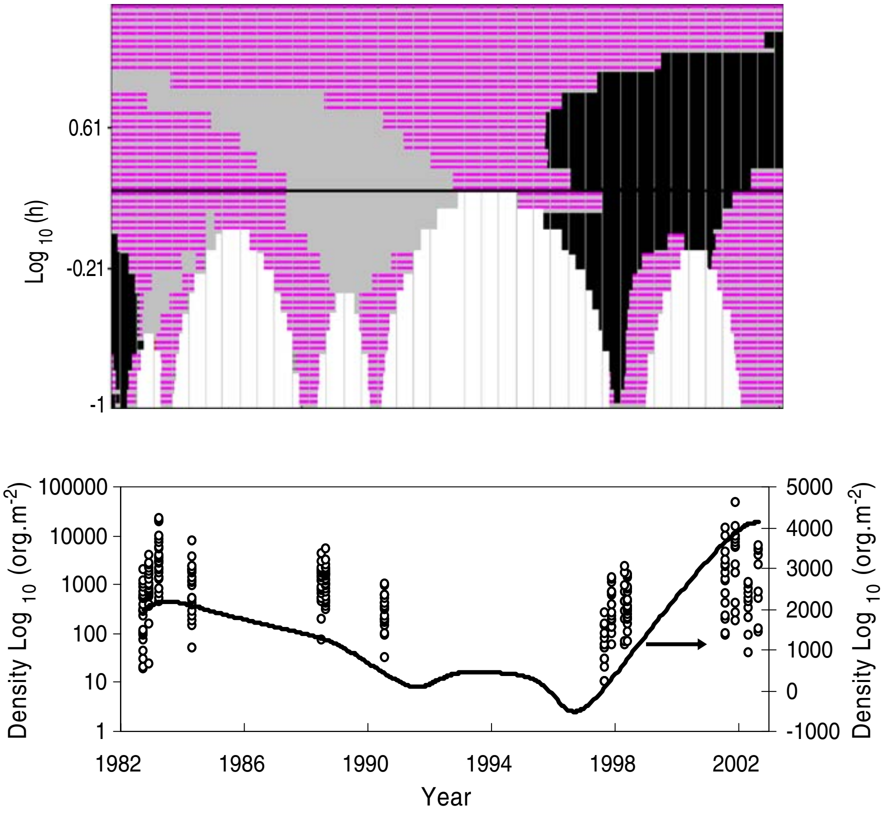


Fig. 2 Temporal trend of mollusks density characteristics in surface sediments

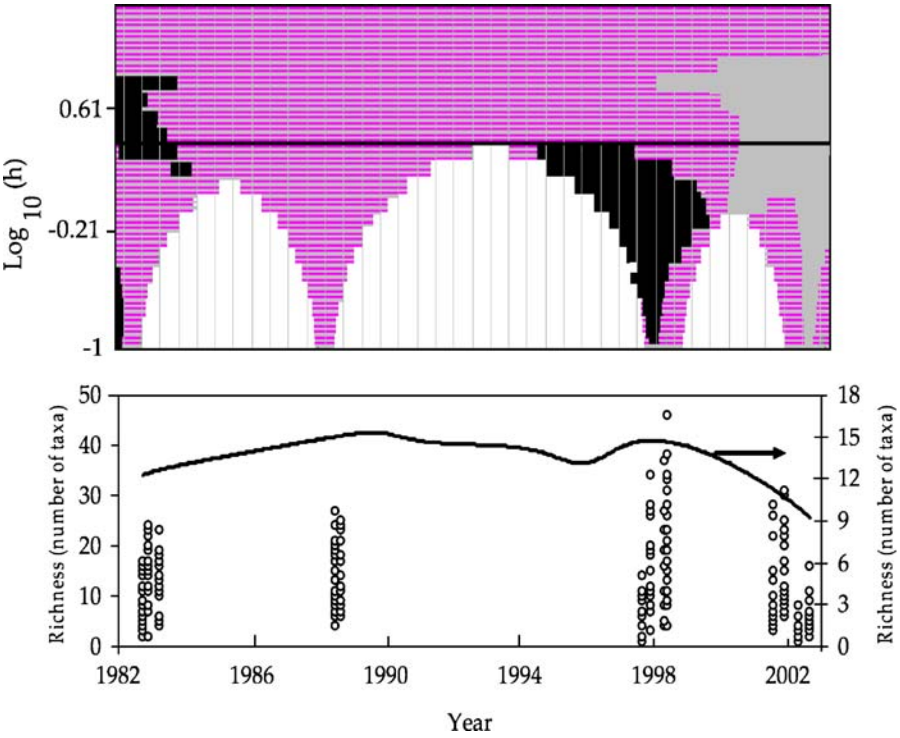


Fig. 3 Temporal trend of mollusks richness characteristics in surface sediments

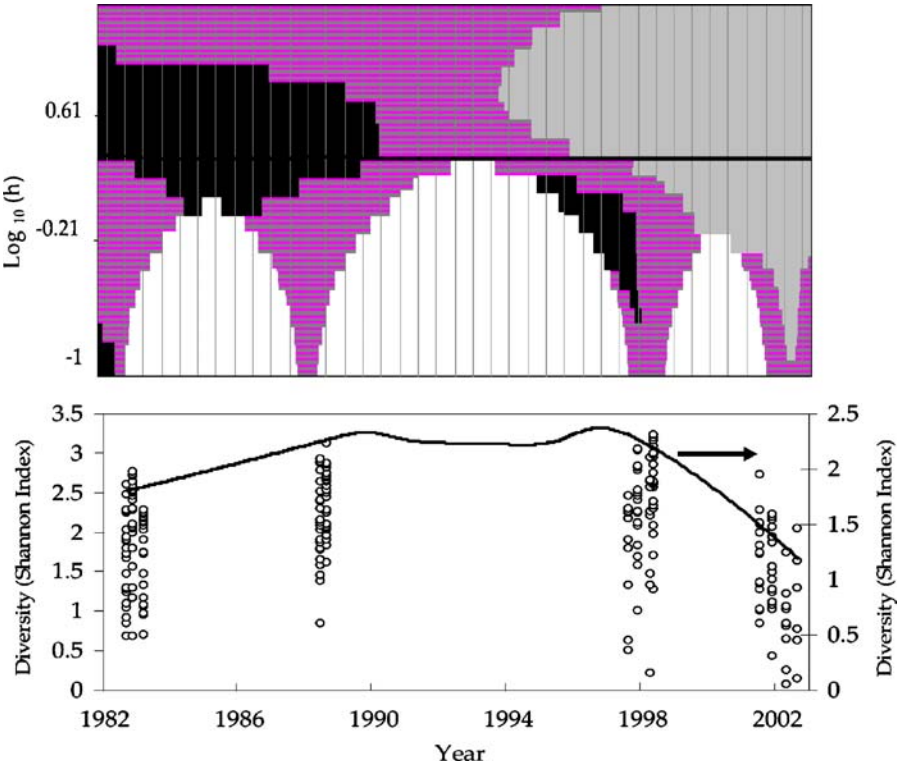


Fig. 4 Temporal trend of mollusks diversity characteristics in surface sediments

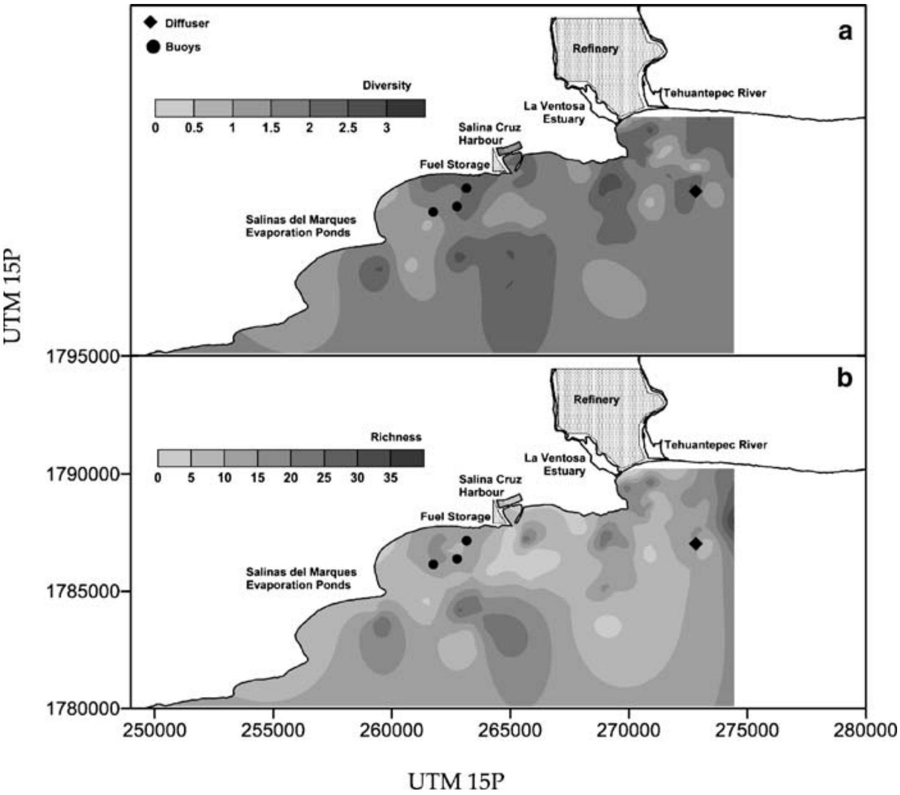


Fig. 5 Reconstructed spatial distribution of **a** diversity and **b** richness mollusks characteristics

Table 4 Explained variance and partial correlations among variables using the ACE models

Variables (x)	Density (y_1)		Variables (x)	Richness (y_2)		Variables (x)	Shannon–Wiener (y_3)	
	% of explained variance	Partial correlation coefficient $\left(pR_B^2\right)$		% of explained variance	Partial correlation coefficient $\left(pR_B^2\right)$		% of explained variance	Partial correlation coefficient $\left(pR_B^2\right)$
x_1=(depth)	4.4148		x_1=(depth)	6.8842		x_2=suspended solids[a]	16.2275	
x_2=suspended solids	8.7263		x_3=percentage of fines	18.3102		x_3=percentage of fines	18.7392	
x_4=Pb[b]	13.7161		x_4=Pb[b]	17.5066		x_4=Pb[b]	23.1896	
x_8=HAT[b]	12.1837		x_5=Cu[b]	10.5109		x_8=HAT[b]	21.7737	
$y_1=x_1, x_2$	20.1734		X_6=Fe[b]	30.0815		$y_3=x_2, x_3$	34.4491	
$y_1=x_1, x_2, x_4$	51.1304	0.3878	X_7=Cr[b]	3.1697		$y_3=x_2, x_3, x_4$	70.9005	0.5561
$y_1=x_1, x_2, x_8$	23.2213	0.0382	x_8=HAT[b]	20.1292		$y_3=x_2, x_3, x_8$	41.2400	−0.5876
			$y_2=x_1, x_3$	29.4515				
			$y_2=x_1, x_3, x_4$	56.1043	0.3778			
			$y_2=x_1, x_3, x_5$	46.3637	0.2397			
			$y_2=x_1, x_3, x_6$	54.8657	0.3602			
			$y_2=x_1, x_3, x_7$	59.9899	0.4329			
			$y_2=x_1, x_3, x_8$	36.3559	−0.6364			

[a] Water

[b] Sediment

characteristics and predictor variables. In the table are include also the calculated partial correlation coefficients for those variables that showed significant shapes correlations.

The ACE bivariate relationships between community characteristics and physicochemical parameters show significant correlations between density and depth, density with suspended solids in water, both showing curves with conspicuous shapes (20.18% of the explained variance). Therefore both were selected to be included in the multivariate models of density vs. physicochemical variables.

In a similar way, richness is associated with depth and the percentage of fines in sediments (29.45% of

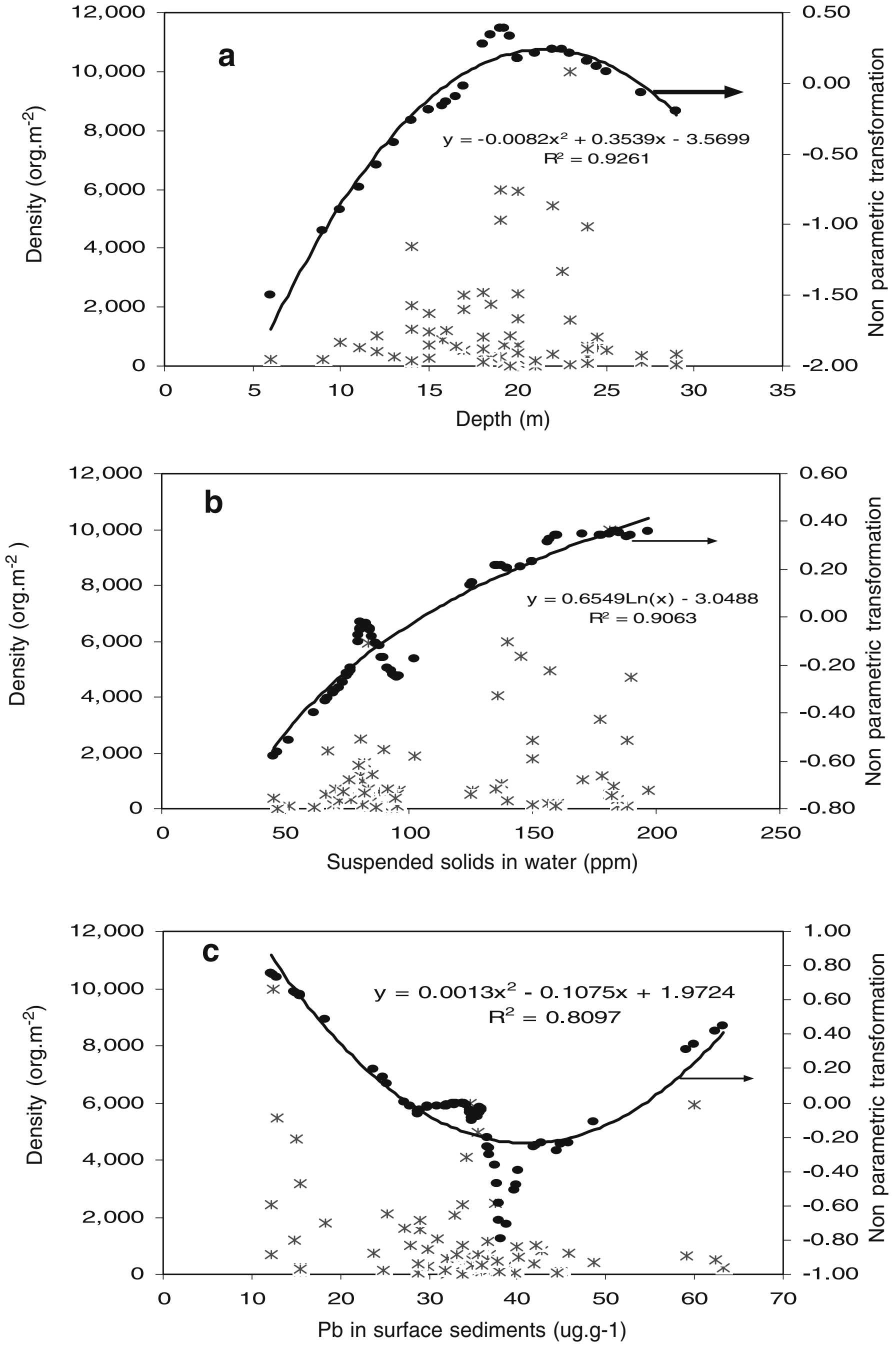


Fig. 6 Variability model for mollusks diversity with **a** depth, **b** suspended solids in water, and **c** Pb concentration in sediments

the explained variance, in the multivariate model). Diversity is associated with suspended solids in water and the percentage of fines in sediments (34.45% of the explained variance in the multivariate model).

The explained variance for density, richness and diversity multivariate models became significantly greater if the concentration of Pb in sediments is included: 51.13%, 56.10% and 70.90%, respectively. In the case of richness, the Cu, Fe and Cr concentrations in sediments, also increase the explained variances, being 60% for Cr.

The impact of Pb on the characteristics of the community based on the partial correlation coefficients analysis can be ordered in decreasing order as: diversity>density>richness, while for this last parameter the impact of metals is Cr>Pb>Fe>Cu.

Mollusks density

The simplest way to understand the shape of the ACE transformation is by means of a plot of the function versus the corresponding data values, i.e. the plots of *Y* and *Y* transformed versus the data values of *X*. Figure 6 display the variability of mollusks density with respect to depth, suspended solids in water, and Pb concentration. The left *Y* scale exhibit the original values of the dependent variable against the predictors (showed with asterisks).

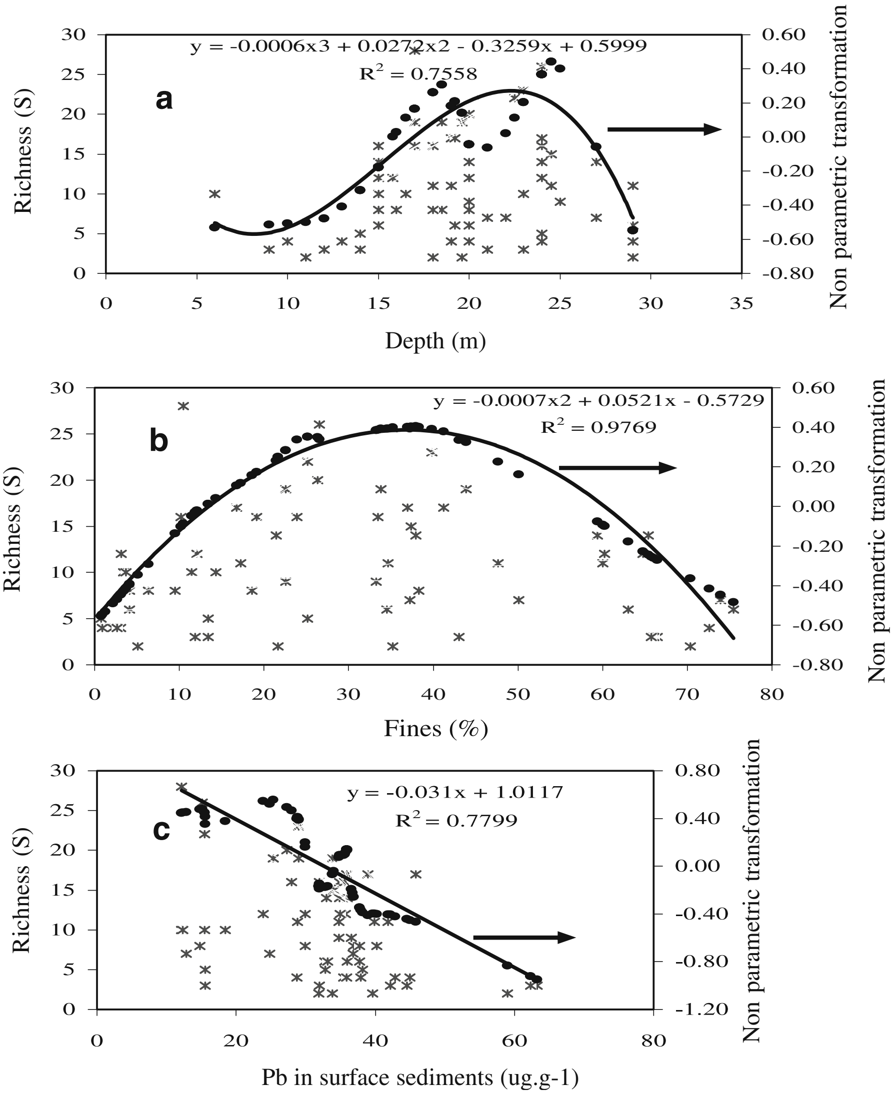


Fig. 7 Variability model for mollusks richness with **a** depth, **b** percentage of fines, and **c** Pb concentration in sediments

The secondary *Y* scale shows the relation between the transformed response variable with the predictors (black circles).

The continuous line shows the adjusted parametric curve of the obtained estimates of the corresponding optimal ACE transformations. On the extent that these transformations are close to the optimal ones, the algorithm produces almost linear functions.

The best adjusted data on Fig. 6c show first a decrease in mollusk density with increasing Pb concentration. The inflection point at 30–40 μg g^{-1} is coincident with the Sediments Quality Guidelines limit for Threshold Effects Level (TEL=30.2 μg g^{-1}) and Effects Range Low (ERL=46.7 μg g^{-1}) reported by MacDonald et al. (1996).

The observed boost in density at Pb>50 μg g^{-1} could be related with a concomitant increase in the abundance of organisms resistant to the metal, as well as an "indirect effect". Increased tolerance of communities to contaminants may result from either population-level responses, such as physiological acclimation and genetic adaptation, or from the replacement of sensitive species by tolerant species (Blanck and Wangberg 1988, Millward and Grant 1995).

"Indirect effects" occurs when contaminant-tolerant species are influenced by the ecological changes that result when some species suffer direct toxic effects. Indirect effects to organisms initiated by chemical contaminants or other stressors, either biotic or abiotic,

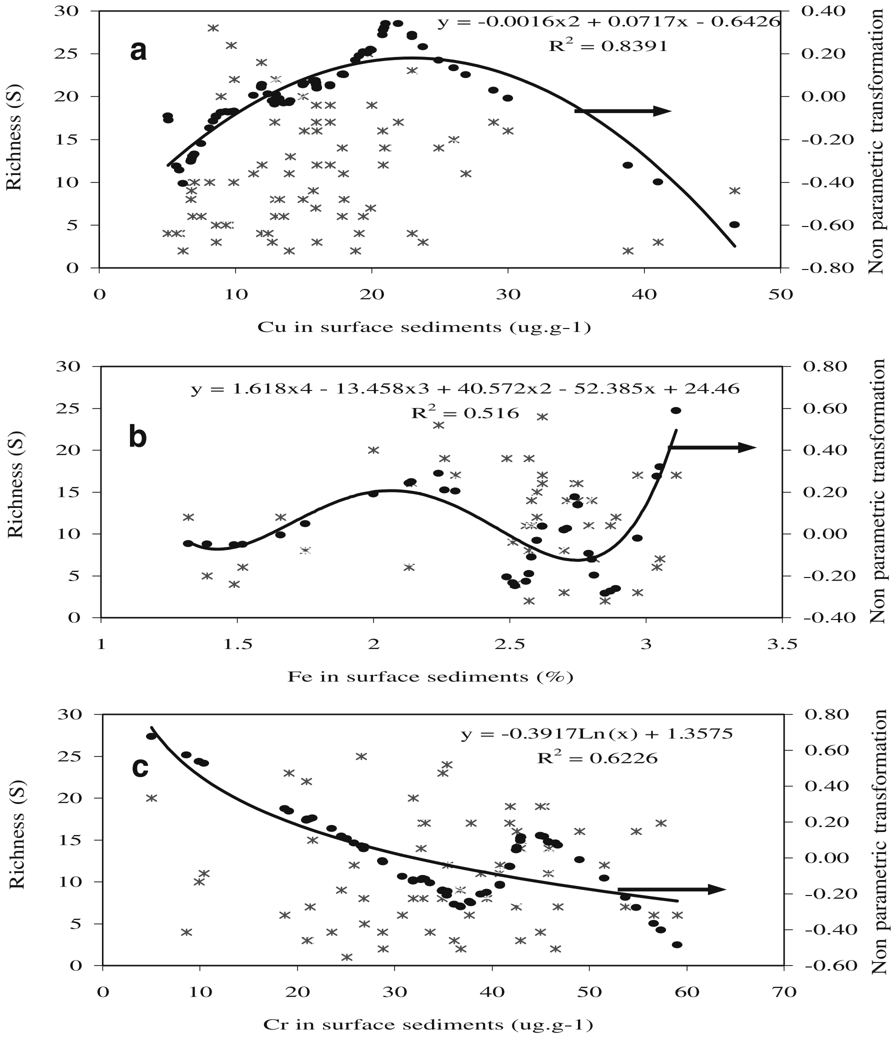


Fig. 8 Variability model for mollusks richness with **a** Cu, **b** Fe, and **c** Cr concentrations in sediments

can be negative (density dependent or independent), or positive (density dependent), may occur between species or within the same species, and could initiate a trophic cascade (Chapman et al. 2003; Fleeger et al. 2003; Chapman 2004).

Mollusks richness

Figure 7 displays the multivariate model results of mollusks richness with respect to depth, percentage of fines, and Pb concentration obtained with the ACE method. Highest richness values are found between 15–25 m depth and 20–45% fines fraction of sediments. The experimental data for Pb show a decrease in the richness variable starting at 35 μg g^{-1} coincident with the TEL and ERL range effect for benthic communities reported by MacDonald et al. (1996).

Figure 8 shows the variability model for mollusks richness with Cu, Fe, and Cr concentrations in sediments. Copper best fitting data shows an increase in richness value up to 20 μg g^{-1}; the inflection point is coincident with the TEL screening level of 18.7 μg g^{-1} reported elsewhere (MacDonald et al. 1996).

Iron presents two maxima at 2.3% and 3% Fe that can be related with species having different Fe requirements to growth in the sediments, or "opportunistic" species, that are capable of re-establishing themselves following disturbance.

Chromium is an important variable that contributes to explain the decrease in richness. The highest richness values ranges between 45 and 50 μg g^{-1}, then a decrease is observed. TEL=52.3 μg g^{-1} has been reported in the Sediments Quality Guidelines for this metal.

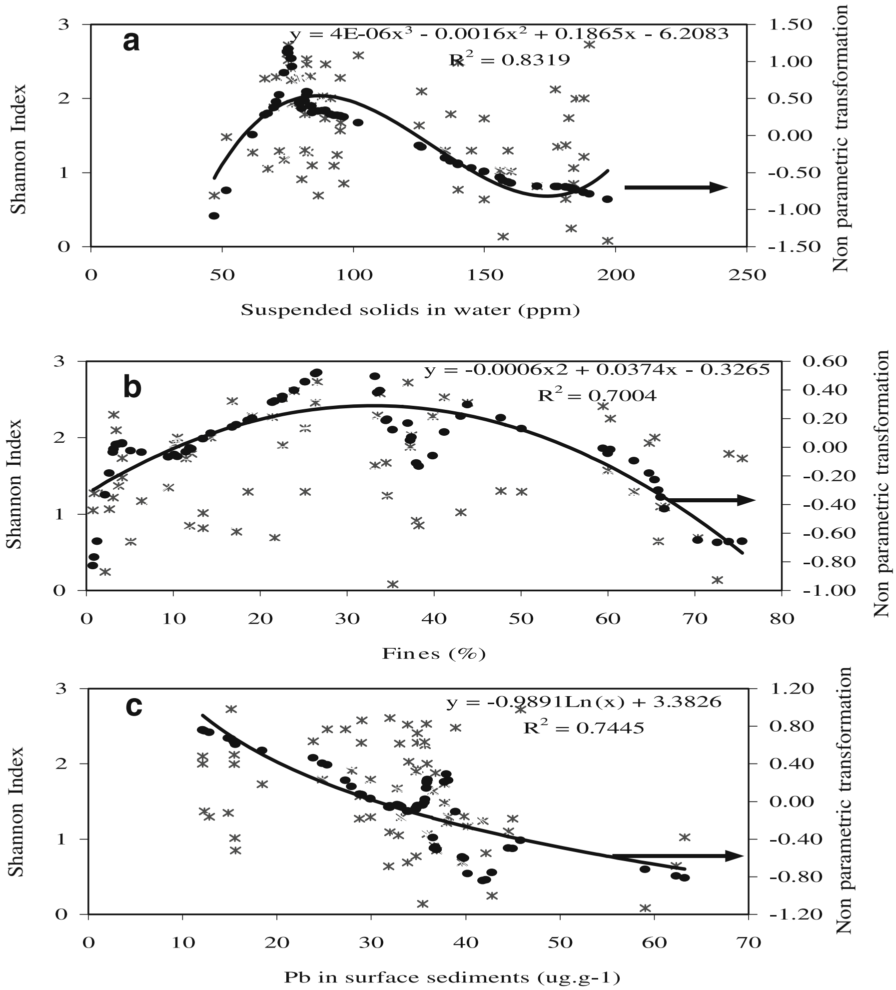


Fig. 9 Variability model for mollusks Shannon Index with **a** suspended solids in water, **b** percentage of fines, and **c** Pb concentration in sediments

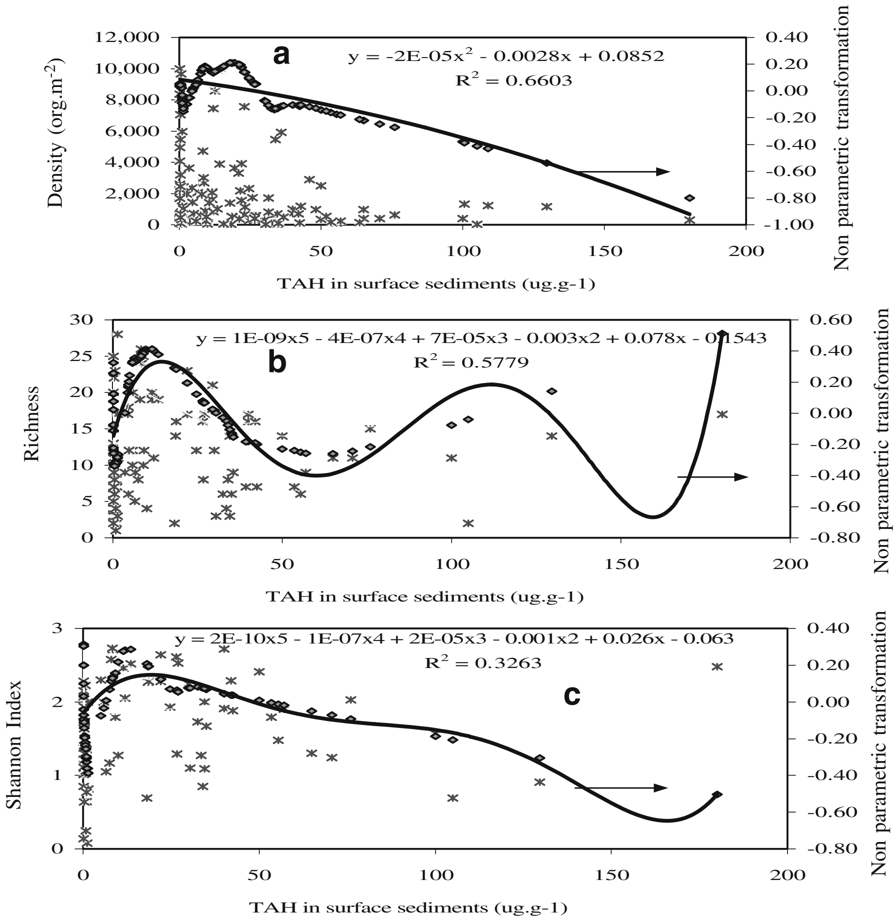


Fig. 10 Variability model for **a** mollusks diversity, **b** richness, and **c** Shannon Index with TAH concentration in sediments

Table 5 List of Important species at 60% of the relative importance value

Class	Super infra order	Family	Genus	Species	Feeding	Density org (m^{-2})	Frequency	RD	RF	RIV
B	Protobranchia	Nuculidae	*Nucula*	*Nucula declivia*	DU	83,618	85	18.13	2.50	10.32
B	Heterodonta	Tellinidae	*Tellina*	*Tellina amianta*	DS	22,623	106	4.90	3.12	4.01
B	Heterodonta	Lucinidae	*Ctena*	*Ctena mexicana*	DC	30,690	28	6.65	0.82	3.74
B	Heterodonta	Lucinidae	*Lucina*	*Lucina mazatlanica*	DC	18,914	95	4.10	2.80	3.45
B	Heterodonta	Veneridae	*Chione*	*Chione subrugosa*	SU	24,190	15	5.24	0.44	2.84
B	Heterodonta	Tellinidae	*Strigilla*	*Strigilla dichotoma*	DS	15,031	81	3.26	2.39	2.82
G	Heterobranchia	Cylichnidae	*Acteocina*	*Acteocina smirna*	CP	17,614	18	3.82	0.53	2.17
G	Littorinimorpha	Caecidae	*Fartulum*	*Fartulum reversum*	HR/HP	13,479	39	2.92	1.15	2.04
B	Pteriomorphia	Mytilidae	*Crenella*	*Crenella divaricata*	SU	11,377	48	2.47	1.41	1.94
G	Neogastropoda	Nassariidae	*Nassarius*	*Nassarius gemmulosus*	CP	7,140	71	1.55	2.09	1.82
B	Heterodonta	Kelliidae	*Bornia*	*Bornia sp1*	SU	5,793	58	1.26	1.71	1.48

Table 5 (continued)

Class	Super infra order	Family	Genus	Species	Feeding	Density org (m^{-2})	Frequency	RD	RF	RIV
B	Heterodonta	Crassatellidae	*Crassinella*	*Crassinella pacifica*	SU	4,551	67	0.99	1.97	1.48
B	Heterodonta	Lucinidae	*Lucina*	*Lucina sp1*	DC	7,906	37	1.71	1.09	1.40
S	Dentaliida	Dentaliidae	*Dentalium*	*Dentalium quadrangulare*	DS/CP	6,500	34	1.41	1.00	1.21
B	Heterodonta	Myidae	*Platyodon*	*Platyodon sp.*	SU	4,642	37	1.01	1.09	1.05
G	Littorinimorpha	Calyptraeidae	*Crepidula*	*Crepidula aculeata*	SU	8,420	8	1.83	0.24	1.03
S	*Gadilimorpha*	Gadilidae	*Cadulus*	*Cadulus sp2*	DS/CP	6,940	18	1.50	0.53	1.02
S	Dentaliida	Dentaliidae	*Dentalium*	*Dentalium sp1*	DS/CP	2,393	49	0.52	1.44	0.98
G	Heterobranchia	Pyramidellidae	*Odostomia*	*Odostomia laxa*	CB	6,450	18	1.40	0.53	0.96
B	Heterodonta	Crassatellidae	*Crassinella*	*Crassinella varians*	SU	2,610	38	0.57	1.12	0.84
G	Littorinimorpha	Caecidae	*Elephantulum*	*Elephantulum inscultum*	HR/HP	6,114	9	1.33	0.27	0.80
B	Heterodonta	Crassatellidae	*Crassinella*	*Crassinella adamsi*	SU	2,890	32	0.63	0.94	0.78
G	Neogastropoda	Terebridae	*Terebra*	*Terebra bridgesi*	CP	3,225	29	0.70	0.85	0.78
B	Heterodonta	Tellinidae	*Tellina*	*Tellina virgo*	DS	3,171	27	0.69	0.80	0.74
B	Heterodonta	Veneridae	*Chione*	*Chione gnidea*	SU	1,889	36	0.41	1.06	0.74
G	Heterobranchia	Retusidae	*Volvulella*	*Volvulella cylindrical*	HM	1,428	36	0.31	1.06	0.69
B	Heterodonta	Cardiidae	*Trachycardium*	*Trachycardium belcheri*	SU	4,150	14	0.90	0.41	0.66
B	Protobranchia	Solemyidae	*Solemya*	*Solemya valvulus*	SU	4,504	10	0.98	0.29	0.64
G	Littorinimorpha	Calyptraeidae	*Calyptraea*	*Calyptraea lichen*	SU	4,740	7	1.03	0.21	0.62
G	Neogastropoda	Nassariidae	*Nassarius*	*Nassarius gallegosi*	CP	2,010	27	0.44	0.80	0.62
G	Littorinimorpha	Naticidae	*Neritina*	*Neritina latissima*	HO/HR	5,100	4	1.11	0.12	0.61
G	Neogastropoda	Olividae	*Olivella*	*Olivella sp2*	CP	1,691	28	0.37	0.82	0.60
G	Ptenoglossa	Eulimidae	*Eulima*	*Eulima panamensis*	CB	1,277	31	0.28	0.91	0.60
B	Heterodonta	Corbulidae	*Corbula*	*Corbula nasuta*	SU	1,383	30	0.30	0.88	0.59
G	Neogastropoda	Nassariidae	*Nassarius*	*Nassarius angulicostis*	CP	2,338	22	0.51	0.65	0.58
G	Heterobranchia	Cylichnidae	*Acteocina*	*Acteocina angustior*	CP	1,366	29	0.30	0.85	0.58
B	Protobranchia	Nuculidae	*Nucula*	*Nucula exigua*	DU	1,280	29	0.28	0.85	0.57
B	Heterodonta	Tellinidae	*Tellina*	*Tellina simulans*	DS	1,130	30	0.24	0.88	0.56
G	Littorinimorpha	Naticidae	*Natica*	*Natica colima*	CP	1,394	27	0.30	0.80	0.55
B	Protobranchia	Solemyidae	*Solemya*	*Solemya sp.*	SU	2,478	19	0.54	0.56	0.55
G	Neogastropoda	Terebridae	*Terebra*	*Terebra armillata*	CP	1,232	28	0.27	0.82	0.55

RD relative density, *RF* relative frequency, *RIV* relative importance value

Mollusks diversity

Diversity, expressed by the Shannon Index is significantly related with suspended solids in water and fines fraction of sediment, reflecting the close associations of contaminants with fine sediments and organic material.

Figure 9 display the ACE plot of the variability of Shannon Index with respect to suspended solids in

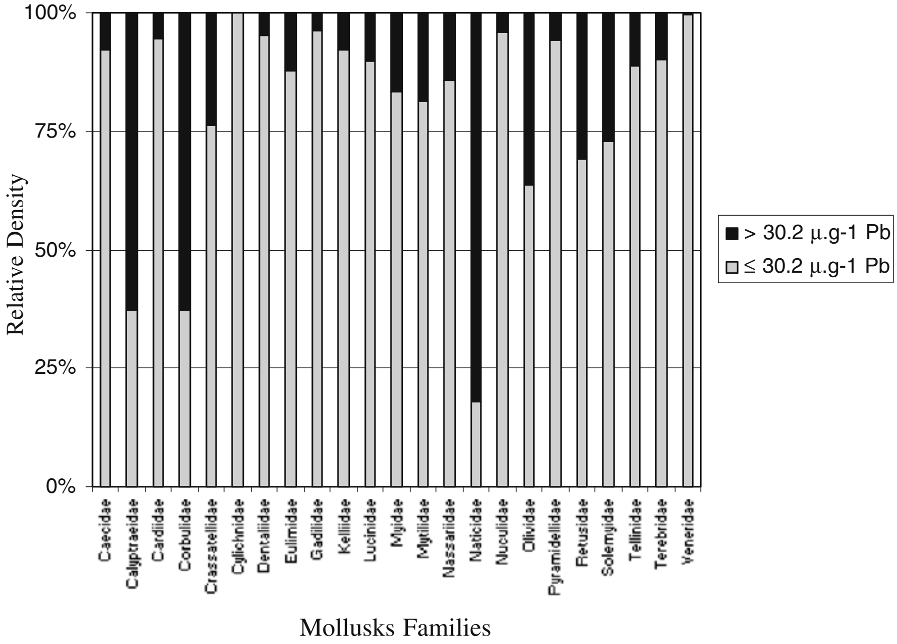


Fig. 11 Mollusks families and their relationship with Pb levels in sediments

water, percentage of fines and Pb concentration. Diversity decrease with Pb and the minimum value of the best fitted data is located between 30 and 40 µg g^{-1}, coincident with the sediments quality guidelines limits for TEL and ERL.

Briefly, time trends mollusk community characteristics show in SiZer maps match the variation presented by the community in relation to Pb were richness and diversity decrease and density increase both along time and related to Pb concentrations.

Organics and mollusks variability

Figure 10 show the plots for density, richness and Shannon Index with respect to TAH concentration in sediments. The ACE method found no significant curves between TAH concentrations and mollusks indicators, which is also presented by the explained variance values presented in Table 3.

Several authors have reported that the classic model of pollution effects on marine macrobenthic

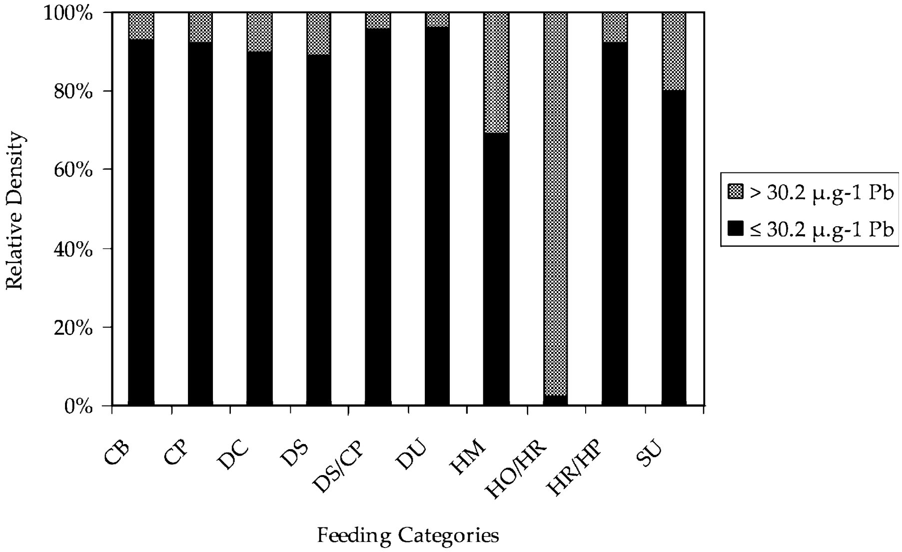
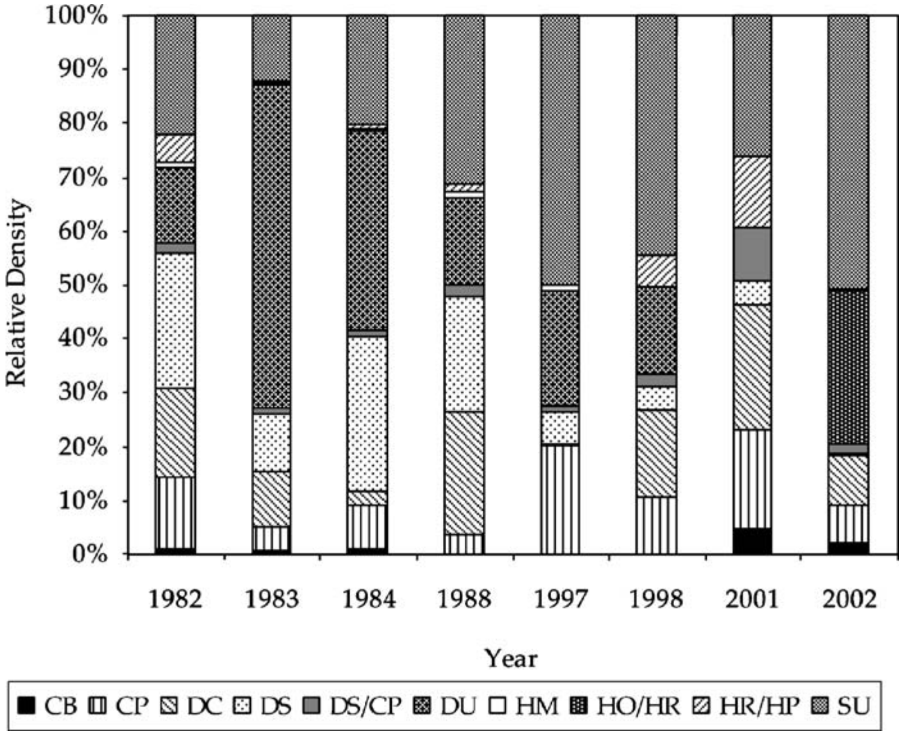


Fig. 12 Mollusks feeding categories and their relationship with Pb levels in sediments

Table 6 Time trends of mollusks families relative densities

Family	1982	1983	1984	1988	1997	1998	2001	2002
Caecidae	5.21	0.24	0.84	1.45		5.91	13.10	0.29
Calyptraeidae							3.87	47.17
Cardiidae							3.11	1.26
Corbulidae	1.40	0.19	0.53	1.46				
Crassatellidae	4.25	2.93	0.90	8.91	8.20	22.00	0.04	2.23
Cylichnidae				1.57	16.02	8.76	13.80	0.11
Dentaliidae	1.68	1.23	0.87	2.32	1.17	2.04	4.47	0.57
Eulimidae	1.12	0.56	1.26					
Gadilidae							5.29	1.43
Kelliidae	7.52	2.38	0.97	1.81		0.41		
Lucinidae	16.77	10.22	2.62	22.92	0.39	16.09	22.97	9.25
Myidae	4.13	3.23	0.20					
Mytilidae	0.67	2.46	16.18	7.94	12.89	7.13		
Nassariidae	6.25	2.97	5.72	1.46			2.45	6.80
Naticidae	1.92	0.66		0.29	0.39		0.09	28.44
Nuculidae	14.20	59.85	37.28	16.16	21.09	16.09		
Olividae	2.80	0.73		0.21				
Pyramidellidae							4.80	2.17
Retusidae	1.01	0.35	0.30	1.18	1.17		0.12	
Solemyidae	3.56	1.04	1.16	10.69				
Tellinidae	24.91	10.65	28.89	21.33	5.86	4.68	4.57	0.29
Terebridae	2.16	0.23	2.08		3.91	1.83	2.20	
Veneridae	0.45	0.08	0.21	0.31	28.91	15.07	19.12	
Feeding category of the Family with higher density	DS	DU	DU	DC	SU	SU	DC	SU

Fig. 13 Time trends of mollusks feeding categories



communities recognizes that species/abundance/biomass curves vary distinctively in a nonlinear manner with the magnitude of organic enrichment (Rakocinski et al. 2000). In Fig. 10, at low levels of organic enrichment, i.e. <50 μg g^{-1}, the mollusks variability indicators are boosted which could be related to the presence of opportunistic species. When TAH is >50 μg g^{-1}, diversity and abundance falls and richness seems to increase following recovery that could be related to the presence of tolerant species.

Important taxa time trends and their relationship with Pb

Important taxa, defined as those comprising 60% of the accumulated relative importance value are presented in Table 5. Important taxa comprise 355,670 organisms per square meter, belonging to 41 taxa, distributed among 3 classes. The bivalves class were the most abundant corresponding to 72% of the density and 21 taxa, followed by the gastropods (24%) and 17 species, finally scaphopoda (3%) with only 3 species. The 41 taxa, corresponds to 28 genus, 23 families, and 9 super infra order.

Relative Importance Values are depicted in the table by decreasing order, therefore the specie *Nucula declivia* has the highest importance value, these taxa is recognized as a subsurface deposit feeder, followed by *Tellina amianta* (a surface deposit feeder) which is the specie with higher frequency value, and finally two chemosymbiotic deposit feeders: *Ctena mexicana* and *Lucina mazatlanica*.

Figure 11 shows important families and their relative density regarding Pb. Values greater than 30.2 μg g^{-1} in accordance with Sediment Quality Guidelines, are considered harmful to benthic biota. In this view, families Naticidae, Calyptraeidae and Corbulidae with relative densities above 50% in sites where Pb level is above this standard, suggest that might be tolerant. Families with relative density below 10% could be considered as sensitive.

Figure 12 shows the feeding categories with respect to Pb levels. According to the data, five feeding categories present densities above the TEL criterion. Four of the categories are herbivorous gastropods which grasp both on fine grained substrates or rock rubble substrates, and in general with scarce sediment relationship. The fifth category is represented by chemosymbiotic deposit feeder bivalves closely related with sediments.

Table 6 shows the families relative density trends along the period of study. High densities are found among the bivalve Crassatellidae, Lucinidae, Tellinidae, and the scaphopod Dentaliidae. In 1983 the bivalve Nuculidae has the higher density, in 1997 was the bivalve Veneridae, and in 2002 the gastropod Calyptraeidae.

In Fig. 13, time trends of mollusks feeding categories are presented indicating that the most important are suspension feeders, subsurface deposit feeders, chemosymbiotic deposit feeders, and surface deposit feeders. From the analysis of this figure is evident that surface deposit feeders are increasing their relative density, while subsurface deposit feeders are decreasing with respect to time, these last are expected to be more related with sediment and more affected then by its quality. However it is important to emphasize that gastropods with predatory carnivore as well as chemosymbiotic deposit feeder bivalves have maintained their relative densities along time.

From the analysis we can conclude that there are changes in the macrobenthic mollusk community structure as well as its trophic structure along the time that could be related with Pb increase levels in sediments.

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