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Biodiversity of polychaetous annelids in Bahía de Todos Santos, Baja California México

OSMAR ARAUJO-LEYVA[1,4*], LUZ VERONICA RODRÍGUEZ-VILLANUEVA[2,5] & JOSÉ VINICIO MACÍAS-ZAMORA[3,6]

[1] *Facultad de Ciencias Marinas, Instituto de Investigaciones Oceanológicas, Universidad Autónoma de Baja California, Carretera Transpenisular Ensenada-Tijuana No. 3917 Fraccionamiento Playitas. C.P. 22860 Ensenada, Baja California, México.*

[2] *Marine Biology Laboratory, Public Utilities Department City of San Diego Ocean, Monitoring Program, 2392 Kincaid Road. 92101 San Diego, CA, USA.*

[3] *Instituto de Investigaciones Oceanológicas, Universidad Autónoma de Baja California, Carretera Transpenisular Ensenada-Tijuana No. 3917 Fraccionamiento Playitas. C.P. 22860, Ensenada, Baja California, México.*

[4] *osmar.araujo@uabc.edu.mx, https://orcid.org/0000-0001-6397-0248*
[5] *lvrodriguez@sandiego.gov, https://orcid.org/0000-0002-3698-4123*
[6] *vmacias@uabc.edu.mx, https://orcid.org/0000-0002-8784-7858*
**Correspondence: osmar.araujo@uabc.edu.mx*

Abstract

The aim of this study was to describe and analyze the structure, distribution, and temporal variation in the composition of benthic polychaeta and their relation to abiotic characteristics in marine sediments along the continental shelf of Bahia de Todos Santos, Baja California, Mexico. Benthic macrofauna and environmental variables were collected to coordinated with a long-term ocean monitoring project known as the Southern California Bight Regional Monitoring Program. A total of nineteen stations were collected in September 1998, twenty stations in November 2003, fifteen stations in December 2013 and sixteen stations in September 2018. These data were compared to assess the response of benthic polychaete assemblages to natural and human induced changes in sediment characteristics. All stations were sampled using a Van Veen grab (0.1 m^2) at depths between 15 to 206 m. Sites were selected using a multiple density nested random-tessellation stratified design. Environmental parameters measured included depth (m), sediment grain size <63µm (%), organic carbon (%), and concentration of metals: Co, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn. A total of 11,854 polychaetous annelids were identified in 43 families, with the numerically dominant families for all years (Spionidae, Chaetopteridae, Cirratulidae, Maldanidae, Onuphidae, and Ampharetidae) accounting for 52.95% of individuals. The best represented families in 1998 were Spionidae, Maldanidae, Ampharetidae and Cirratulidae. In 2003 the best represented families were Spionidae, Maldanidae, Cirratulidae, and Onuphidae; in 2013 Chaetopteridae and Spionidae; and in 2018 Spionidae, Ampharetidae, Syllidae and Cirratulidae. The Bio-Env multivariate analysis showed that the factors that most correlated with the abundance and richness of families and had the greatest influence over spatial distribution trends for community structure were %Organic carbon and Cu concentration during 1998, % Organic carbon and depth in 2003 and Pb concentration in 2013.

Key words: polychaetes, biodiversity, community, sediment, treatment plants

Introduction

Marine ecosystems in Baja California are under threat or pressure by different sources such as urban expansion along the coast, industrial activities, marine tuna net-pen farming and shellfish aquaculture that have experienced growth over recent decades. Human activities vary in their intensity of impact along different spatial and temporal scales on the ecological condition of communities, including modification or loss of habitat, overexploitation of living resources, and degradation of water quality. Wastewater treatment plants, industrial discharges, atmospheric fallout and many non-point effluents like urban stormwater runoff are sources of pollution to

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the coastal water areas that introduce synthetic-organic compounds, heavy metals, hydrocarbons, and various inorganic chemicals. In bays such as Bahia de Todos Santos, due to weather conditions, pollutants may build-up on impervious surfaces during the extended dry seasons, and subsequently wash-off into the ocean once the wet season begins. Atmospheric deposition may be especially important as a source of pollutants to stormwater effluents in these regions because significant quantities of trace metals and other pollutants are emitted into the atmosphere daily, depositing onto the water column and rapidly being removed and transported to bottom sediments (Macías-Zamora 1996; Macías-Carranza *et al.* 1997; Schiff 2000; Chong & Wang, 2000; Macías-Zamora *et al.* 2002; Lenihan *et al.* 2003; Sabin *et al.* 2005; Macías-Zamora *et al.* 2016; Macías-Zamora *et al.* 2018).

Benthic macroinvertebrates are relatively sedentary fauna, they live within or on the surface of the sediments (i.e., infauna and epifauna, respectively), and therefore cannot easily avoid exposure to pollutants and other adverse conditions in their immediate surroundings. In addition, correlations between environmental factors and benthic community structure often provide useful measures of anthropogenic impact. Severely degraded sites either have few organisms and dominance of one species or an unbalanced community, heavily dominated by a small number of species, usually annelid worms. Benthic organisms are a good indicator of system health because conditions are integrated over time through multiple generations (Pearson & Rosenberg 1978; Hyland *et al.* 1999; Wazniak C. & Llansó R., 2004). The group of organisms analyzed in this study are benthic polychaete communities, because they are the numerically dominant macrobenthic taxon in soft-bottom sediments, both with regard to the number of species and abundance, and may constitute more than half of the organisms in soft-bottom habitats.

Polychaetes are also known to be relatively tolerant of silting and hydrodynamic conditions compared to most other groups of benthic organisms. The presence or absence of specific polychaetes on marine sediments therefore provides an indication of the condition or health of the benthic environment, and they have been extensively applied in environmental monitoring programs throughout the world (Fauchald & Jumars, 1979; Pearson & Rosenberg, 1978; Gambi & Giangrande, 1986; Crema *et al.* 1991;Pocklington & Wells 1992; Gray *et al.* 1992; Inglis & Kross, 2000; Samuelson, 2001; Solis-Weiss *et al.* 2004; Hilbig & Blake, 2006; Olomukoro & Azubuike 2009; Neave *et al.* 2013).

However, the lack of spatial and temporal benthic community studies makes it difficult to understand what has changed in a given habitat. Long-term studies not only provide information about the consequences of an activity, but also give the responsible parties the opportunity to take appropriate measures to mitigate or prevent negative effects on the environment. Polychaete communities are influenced by many physical, chemical, and biological factors. These include the various attributes of bottom waters (e.g., temperature, salinity, dissolved oxygen, current velocity) and sediments (e.g., particle size distribution, sediment chemistry), as well as biological factors such as food availability, competition, and predation. These factors are affected by both natural processes and human activities, which ultimately determine the structure of benthic communities (Macías-Zamora 1996; Rodriguez-Villanueva *et al*. 2003; 2005; Ramírez-Alvarez *et al.* 2007; Alvarez-Aguilar *et al.* 2017). Our assessment and understanding of ecological effects on habitat alteration and the impact to benthic marine communities will improve our ability to detect and develop proper strategies for mitigating the impacts of discharge of anthropogenic chemical contaminants into marine ecosystems (Ramos *et al.* 2004; Lenihan *et al.* 2003).This study reviews the past four benthic surveys in Bahia de Todos Santo Baja California Mexico, and how these benthic communities have changed over time, their spatial distribution and temporal resolution, focusing on marine polychaetes from soft-sediment habitats. Sampling years coincided with the region-wide Southern California Bight project (1998; 2003; 2013 and 2018), an ongoing multi-organization marine monitoring collaboration that studies more than 1500 square miles of Southern California coaster waters.

Material and methods

Study area—Bahía de Todos Santos is located approximately 100 km south of the United States-Mexico border region, within the southern part of the Southern California Bight (SCB) on the northwest coast of Baja California, Mexico between 31°40′ - 31°56′ N; 116°36′ - 116°56′ W (Fig. 1). Bahía de Todos Santos is bounded by Punta San Miguel to the north, Punta Banda to the south, and two small islands called Islas de Todos Santos to the west.

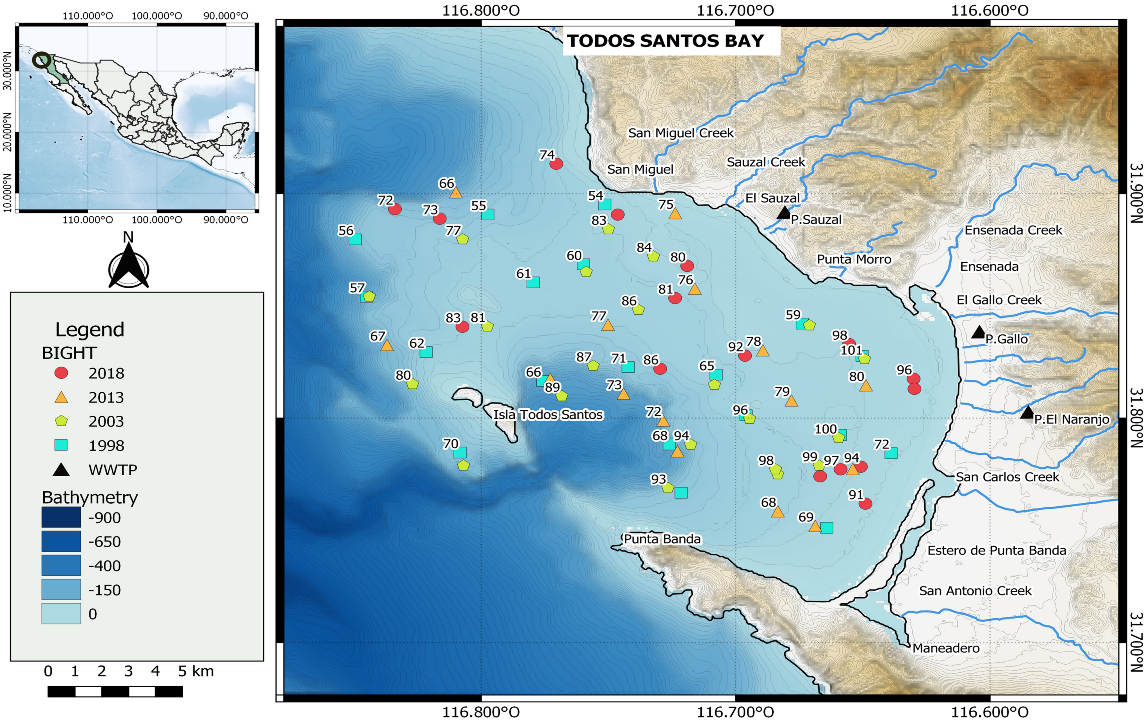

FIGURE 1. Map of the study area showing location of station sampled for each oceanographic survey 1998–2018 in Bahía de Todos Santos, B.C. Mexico, located at the southernmost portion of the Southern California Bight.

The division created by these islands gives the bay two distinct entryways with different submarine topographies. The entrance to the northeast is 12 km wide, with depths under 50 m, and shallows down to 6 m. The southeast entrance is 6 km wide, with steep walls due to a submarine canyon (Todos Santos canyon) which has a depth of 400 m and lies between Punta Banda and Islas de Todos Santos. To the southeast, the bay is bounded by Estero Punta Banda (Fig. 1). The approximate surface of the bay is 240 km^2 with close to 90% of this area between 10 to 100 m in depth, except for the canyon area (Secretaría de Marina, 1974; Gavidia, 1988; Argote-Espinoza *et al.* 1991; Smith, *et al.* 2008). In the inner part of the bay, the city of Ensenada is located, with 486,639 inhabitants recording in 2015 (INEGI, 2015), which is more than double the population of 203,000 that it had in 2000 (INEGI, 2000). Bahía de Todos Santos has been affected by point discharges that have direct input into the coastal waters, for example two wastewater discharges, El Gallo wastewater treatment plant (WWTP) and El Naranjo WWTP, also five creeks run into the bay system directly: El Carmen, Ensenada, El Gallo, San Carlos and San Antonio (Avila, 1983; Romero-Vargas Marquez, 1995; Gutiérrez-Galindo *et al.* 2010). Non-point sources to the system are fishing and boat traffic, dredging and disposition of dredged materials from Ensenada harbor and El Sauzal harbor, bivalve aquaculture of the mussels *Mytilus galloprovincialis*, *Mytilus edulis* and *M. californianus* and the oysters *Crassostrea gigas* and *Crassostrea sikamea* and also floating cage tuna farming (Smith *et al.* 2008). The pattern of circulation within the bay generally consists of an influx of water from the north and south. In both zones water circulation follows the contour of the coast, forming a cyclonic gyre to the south and an anticyclonic gyre to the north. This leads to a notable convergence adjacent to the mouth of Estero Punta Banda along the eastern shore (Argote-Espinoza *et al.* 1975; 1991; Alvarez-Sánchez *et al.* 1988), and sediment transport into and within the bay follows the same circulation pattern (Pérez-Higuera & Chee-Barragan 1984). The prominence of Punta Banda, submarine canyons to the north and south of the bay, and a very narrow shelf outside the bay, make it unlikely that there is a large amount of alongshore sediment delivery to the bay from either the north or south (Fig. 1). Upwelling has local effects on water properties (including temperature, nutrients, and chlorophyll) near the mouth of Bahía de Todos Santos during the spring (Espinosa-Carreón *et al.* 2001; Smith, *et al.* 2008). Mean surface temperature in the bay ranges from 11°C in February to 22.5°C in August and September. Surface salinity ranges from 33.7 ‰ in winter to 33.3 ‰ in summer (Mancilla &- Martinez, 1991). Fluctuation of these variables at different times of the year indicate the influence of different water masses each with its own hydrologic conditions, and the impact of the California current in the bay (Garcia-Cordova, 1983; Millan-Nuñez & Loya-Salinas, 1993). The pattern of sediment distribution in the bay, according to Walton (1955), Emery & Stevenson (1957), and Riveroll-Schroeder (1985), is characterized by three prime groups: Group I sediments of very fine sand to medium sand; Group II sediments of coarse mud to fine sand; Group III sediments of medium mud to fine clay.

Data collection and processing samples—Sediments were sampled during four different El Niño-Southern Oscillation (ENSO) events with corresponding intensity conditions and were carried out aboard the research vessels "Alguita" and "Suchiate" during four oceanographic cruises. In September 1998, 19 stations were sampled, in December 2003 20 stations were sampled, in October 2013 15 stations were sampled, and in September 2018 16 station were sampled. A total of 70 stations were sampled using a Van Veen (0.1 m^2) grab in depths ranging between 15 to 206 m (Fig. 1). To define sample stations a multiple density nested random-tessellation stratified design was utilized (Stevens, 1997). This MD-NRTS is a method used for populations distributed in continuous fashion that measures environmental conditions at a regional scale. This method is based on a random stratified design that considered 3 strata: depth, continental platform amplitude, and proximity to potential sources of anthropogenic impact. Two grabs were taken per station, the first to analyze the macrofaunal community, and the second to analyze the chemical characteristics of the sediment.

Samples for benthic macrofauna were sieved aboard ship through a 1.0 mm mesh screen, and all organisms retained were placed in labeled plastic containers, relaxed for 30 minutes in $MgSO_4$ solution, and tissue was fixed in 10% borax-buffered formalin. In the laboratory each macrofauna sample was thoroughly washed with freshwater through a 1.0 mm mesh sieve to retain macroinvertebrates; those retained were placed in a Petri-dish with 70% Ethyl alcohol for sorting using a stereoscopic microscope. For this study all polychaetes were separated, classified and identified to family level using taxonomic keys that included Fauchald (1977), Salazar-Vallejo *et al.* (1989) and Blake *et al.* (1994, 1995, 1996). From the second grab, three separate 200 g samples subsamples were collected to measured sediment grain size <63µm (%), percentage of organic carbon, and trace metal concentrations. All sediment chemistry samples were collected using a Teflon spatula, stored in previously acid-washed polypropylene centrifuge flasks, and kept frozen prior to analysis. For measurements of trace metal concentrations, the sediment samples were digested and processed according to the method 3050B from SW-846 protocol of the Environmental Protection Agency (EPA 1996). The analysis included the following trace metals plus iron as a normalizing agent: Co (µg/g), Cr (µg/g), Cu (µg/g), Fe (µg/g), Mn (µg/g), Ni (µg/g), Pb (µg/g), and Zn (µg/g); metals were quantified using air-acetylene flame atomic absorption with a Varian Spec-trAA 240 FS. Sediment grain size distribution (GS) (%< 0.63 µm) was determined using a Horiba (model LA-910) laser/tungsten particle size analyzer according to the methodology described by Daesslé *et al.* (2002). A LECO (model CHNS-932) carbon analyzer was used to determine percentage of organic carbon (% OC) (Schiff & Weisberg, 1999). Sediment chemistry analysis for the sample year 2018 were not available at the time of publication.

Data analysis

Environmental variables—Environmental parameters measured from each station (i.e. depth, organic carbon, sediment grain size and heavy metal concentrations) were standardized and normalized, then evaluated with multivariate statistical analyses. To understand the spatial distribution of environmental parameters Euclidean distances coefficient were calculated based on environmental/abiotic data resulting in a correlation matrix of eleven environmental variables: depth (m), organic carbon (%), sediment grain size <63µm (%), and heavy metal characteristics Co (µg/g), Cr (µg/g), Cu (µg/g), Fe (µg/g), Mn (µg/g), Ni (µg/g), Pb (µg/g), and Zn (µg/g). Principal Components Analysis (PCA) was applied to the correlation matrix with all the sampling stations for each year sampled. The analysis was applied using various routines in PRIMER-E v6 software (Clarke & Gorley, 2006).

Benthic polychaete communities—Differences between the sampled sites at spatial and temporal scales was examined using univariate community parameters, such as abundance (ind./0.1 m^2), family richness (S), Shannon-Wiener diversity index (H' log2); Pielou's evenness index (J') and Simpson's dominance index, (Frontier, 1985; Ludwig & Reynolds, 1988; Pielou, 1977; Odum *et al.*, 1979). The statistical analyses were performed using various routines in the PRIMER-E v6 software (Clarke & Gorley, 2006). Shannon-Wiener diversity index integrates species richness as well as equitability of the community. The diversity index can usually take values between 0 and 5 bits/individual (Marques *et al.* 2009). Molvaer *et al.* (1997) established the following relation between the Shannon-Wiener index values and the different levels of ecological quality, in accordance with the Framework Directive (WFD, 2000/60/EC). High status >4 bits/ind.; Good status 4-3 bits/ind.; Moderate status 3-2 bits/ind.; Poor status 2-1 bits/ind. and Bad status 1-0 bits/ind.

Multivariate analyses of the data such as ordination and classification methods were used to measure the level of association or similarity of different sample sites and detect spatial patterns among the composition and abundance of the polychaete community. The analyses were applied using PRIMER-E v6 software (Warwick & Clarke, 1991; Clarke, 1993; Clarke & Warwick, 1994**;** Clarke & Gorley, 2006). A similarity matrix was constructed using the Bray-Curtis similarity coefficient after square root transforming family abundance data. An ordination space non-metric multidimensional scaling (nMDS) was constructed employing the Bray-Curtis similarity coefficient to visually depict relationships among sites. Similarity percentage analysis (SIMPER) was used to explore the taxa contribution to similarity between the groups formed. The Analysis of similarity between groups (ANOSIM) was carried out using Bray-Curtis distances calculated from relative abundance data, with 1000 Monte Carlo permutations. ANOSIM ($\alpha = 0.05$) was performed to evaluate differences between sample years. The environmental variables, as well as the community structure of the polychaete fauna, were analyzed using BIO-ENV analysis which selects a variable or combination of variables which best explained the differences in polychaete community structure.

Results

Environmental characteristics of sampled sites—Principal Component Analysis (PCA) applied to twelve environmental variables measured during the 1998 oceanographic survey indicated that they explained 69.7% of the total environmental variation in the first two axis (Table 1). The first component (PC1) explained 54.2% of the variance and was highly influenced by the values of Cd (µg/g) and Cu (µg/g) present in the area (Fig. 2A). The second component (PC2) was determined by sediment grain size <63µm (%), and Co values (µg/g), explaining 15.5% of the variance. The ordination chart shows a spatial distribution that strongly correlated with the high concentrations of Cd(µg/g) (Fig. 2A).

In 2003 the eleven measured environmental variables explained 79.6% of the accumulated variance in the first two axes (Table 1). The first component (PC1) explained 66.9% of the variance and was highly influenced by Cr (µg/g) and Mn (µg/g) (Fig. 2B). The second component (PC2) explained 12.7% of the variance, and the greatest influence was given by Fe (µg/g) and depth (m). The ordination chart shows a spatial distribution of stations 78, 83, 87, 89, 94 and 99 with high concentrations of Cr (µg/g), Mn (µg/g) and Fe (µg/g) detected in the shallow (stations 83, 87 and 99); middle (station 94), and deep (stations 89, 78) areas of the bay (Fig. 2B).

TABLE 1. Results of PCA analysis for 12 environmental variables measured. The eigenvalues and eigenvectors of the first 2 PCs are shown; variables with the highest value are marked in yellow.

	Survey					
Variable	98		2003		2013	
	PC1	PC2	PC1	PC2	PC1	PC2
<63um	-0.171	**0.489**	-0.253	0.296	-0.292	-0.149
CO%	-0.327	0.212	-0.281	0.490	-0.292	0.040
Cd	**-0.338**	0.002	-	-	-0.263	**0.567**
Co	-0.174	**-0.437**	-0.315	0.025	**-0.299**	-0.059
Cr	-0.340	0.107	**-0.342**	-0.089	-0.281	-0.242
Cu	**-0.338**	0.105	-0.336	-0.134	**-0.299**	-0.034
Fe	-0.314	0.203	-0.246	**-0.521**	-0.263	**-0.573**
Mn	-0.328	-0.083	**-0.334**	-0.236	**-0.302**	-0.167
Ni	-0.294	-0.306	-0.329	0.074	-0.297	0.197
Pb	-0.170	-0.560	-0.291	-0.281	-0.290	0.148
Zn	-0.260	0.167	-0.328	0.019	-0.295	-0.125
Depth	-0.317	-0.140	-0.235	**0.483**	-0.287	**0.399**

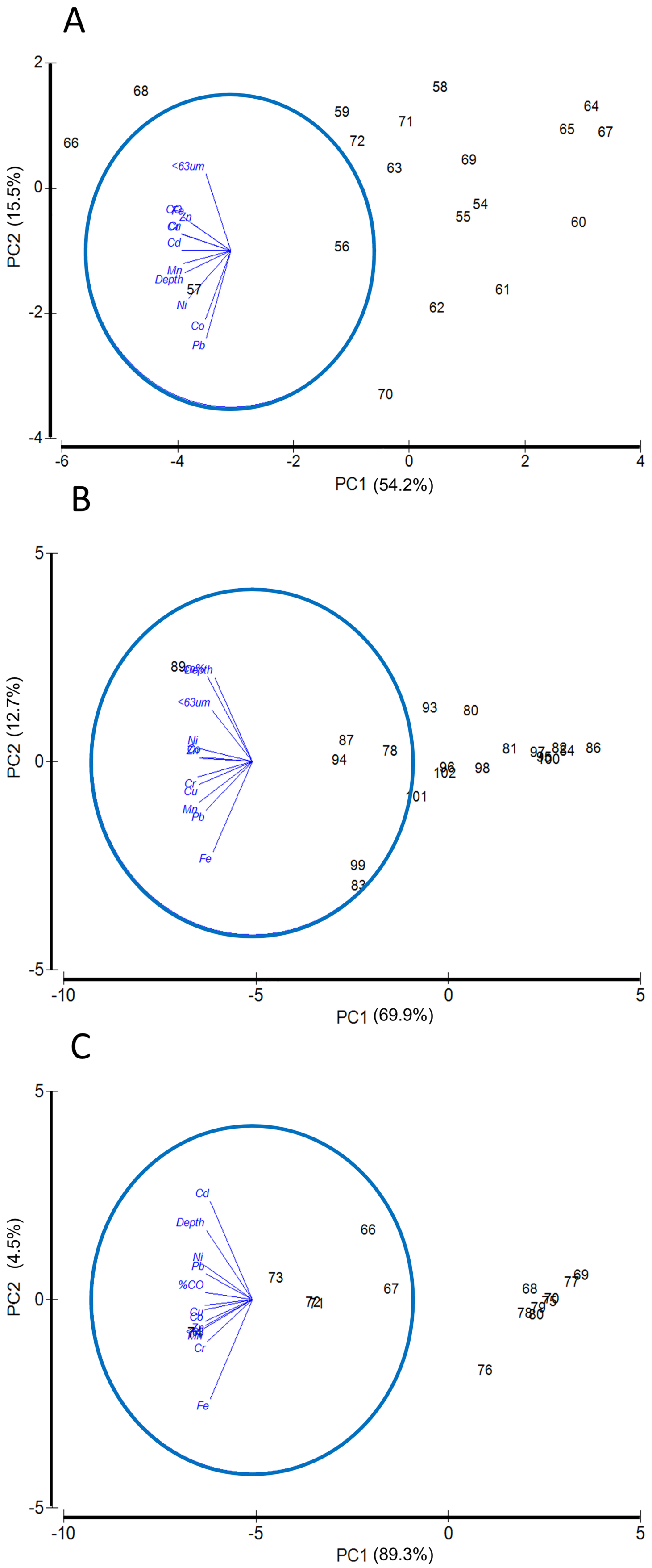

FIGURE 2. Graph of Principal components analysis (PCA) ordination of sampled stations based on a Euclidean Distances matrix considering 12 environmental variables measured in Bahia de Todos Santos. (A) 1998; (B) 2003; (C) 2013.

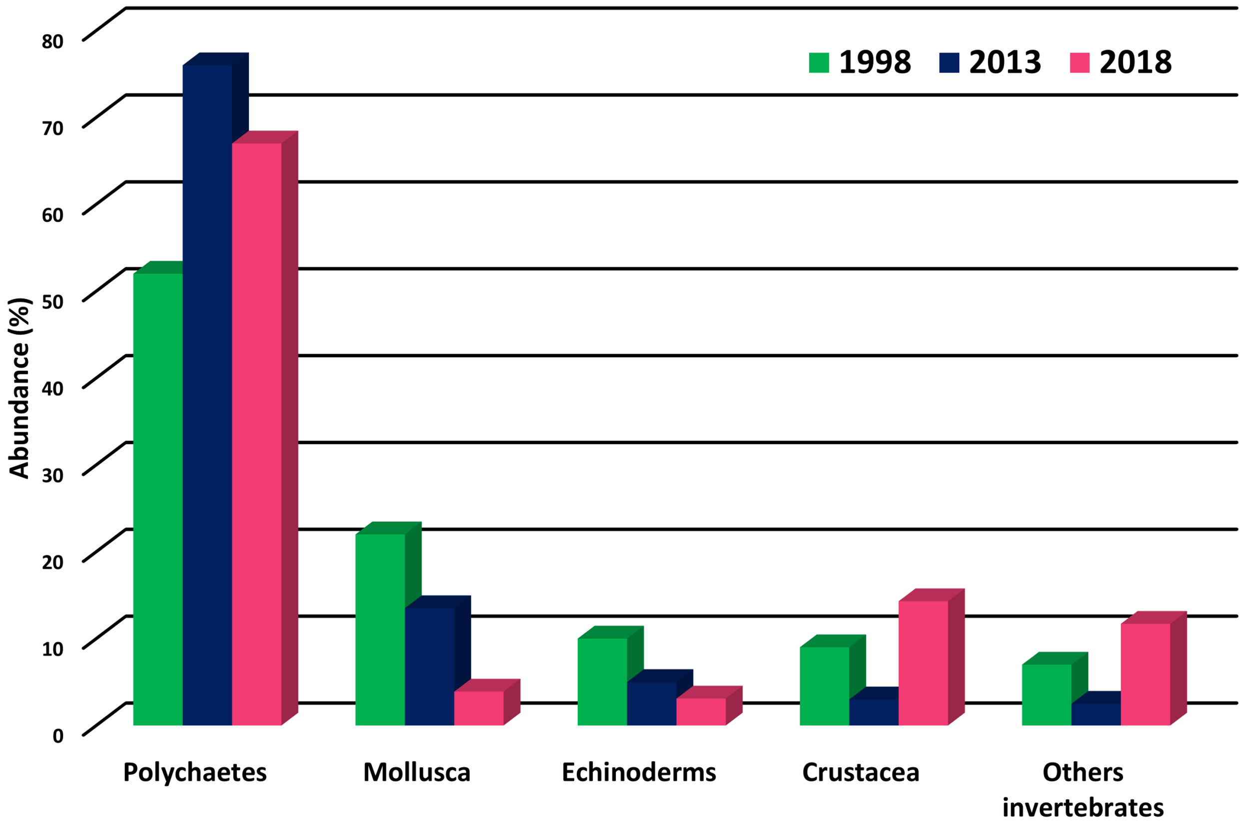

FIGURE 3. Faunistic composition of the benthic macrofauna in Bahia de Todos Santos. Polychaetous annelids dominated community structure constituting 57%, 76% and 67% of the total macrofaunal for 1998, 2013 and 2018.

In 2013 the twelve measured environmental variables explained 93.8% of the accumulated variance in the first two axes (Table 1). The first component (PC1) explained 89.3% of the variance and the variables that influenced most were Mn (µg/g), Cu (µg/g), and Co (µg/g) (Fig. 2C). The second component (PC2) explained 4.5% of variance and the variables that had the greatest influence were Fe (µg/g), Cd (µg/g) and depth (m). The ordination graph shows a spatial distribution of stations 72, 73, 74, 66 and 67 strongly correlated with high values of Cu (µg/g), Co (µg/g) and Mn (µg/g), for the rest of the stations, located at the north entrance of the bay and near the submarine canyon (Fig. 2C).

In general, we observed a temporal trend, where there was a better explanation of variance of the environmental variables over time as the oceanographic surveys advanced (1998, 2003 and 2013). Although for 1998, the spatial distribution of metals was mostly influenced by percentage of sediment grain size <63µm, while for 2003 and 2013 this spatial distribution was more influenced by depth (m) (Fig. 2).

Composition of the community structure between sampling sites—During 1998, 2013 and 2018 surveys, five large faunal groups including Mollusca, Annelida, Crustacea Echinodermata, and Other Invertebrates (Cnidaria, Sipuncula, Phoronida, Chordata, etc.) were identified. The annelids (Class Polychaeta) dominated community structure constituting 52% (1998), 76% (2013) and 67% (2018) of the total benthic macrofauna. Polychaetes presented the greatest abundances with 1175 (1998), 6764 (2013) and 2245 (2018) ind./0.1 m^2. For 1998 the rest of the non-polychaete macrofauna was made up of the Phylum Mollusca with 497 ind./0.1 m^2 (22%), Phylum Echinodermata with 122 ind./0.1 m^2 (10%), Subphylum Crustacea with 201 ind./0.1 m^2 (9%), and other invertebrates 160 ind./0.1 m^2 (7%) (Fig. 3). A change in abundance and community structure was observed in 2013, for the non-polychaete benthic macrofauna, observing more than double in abundance for Mollusca with 1210 ind./0.1 m^2 (14%), Crustacea with 448 ind./0.1 m^2 (5%), Echinodermata with 260 ind./0.1 m^2 (3%), and other invertebrates with 160 ind./0.1 m^2 (3%) (Fig. 3). A change in the community structure is observed for 2018, with respect to the rest of the non-polychaete benthic macrofauna, a doubling in the abundance of Crustacea with 480 ind./0.1 m^2 (14%), and Other Invertebrates with 395 ind./0.1 m^2 (12%).

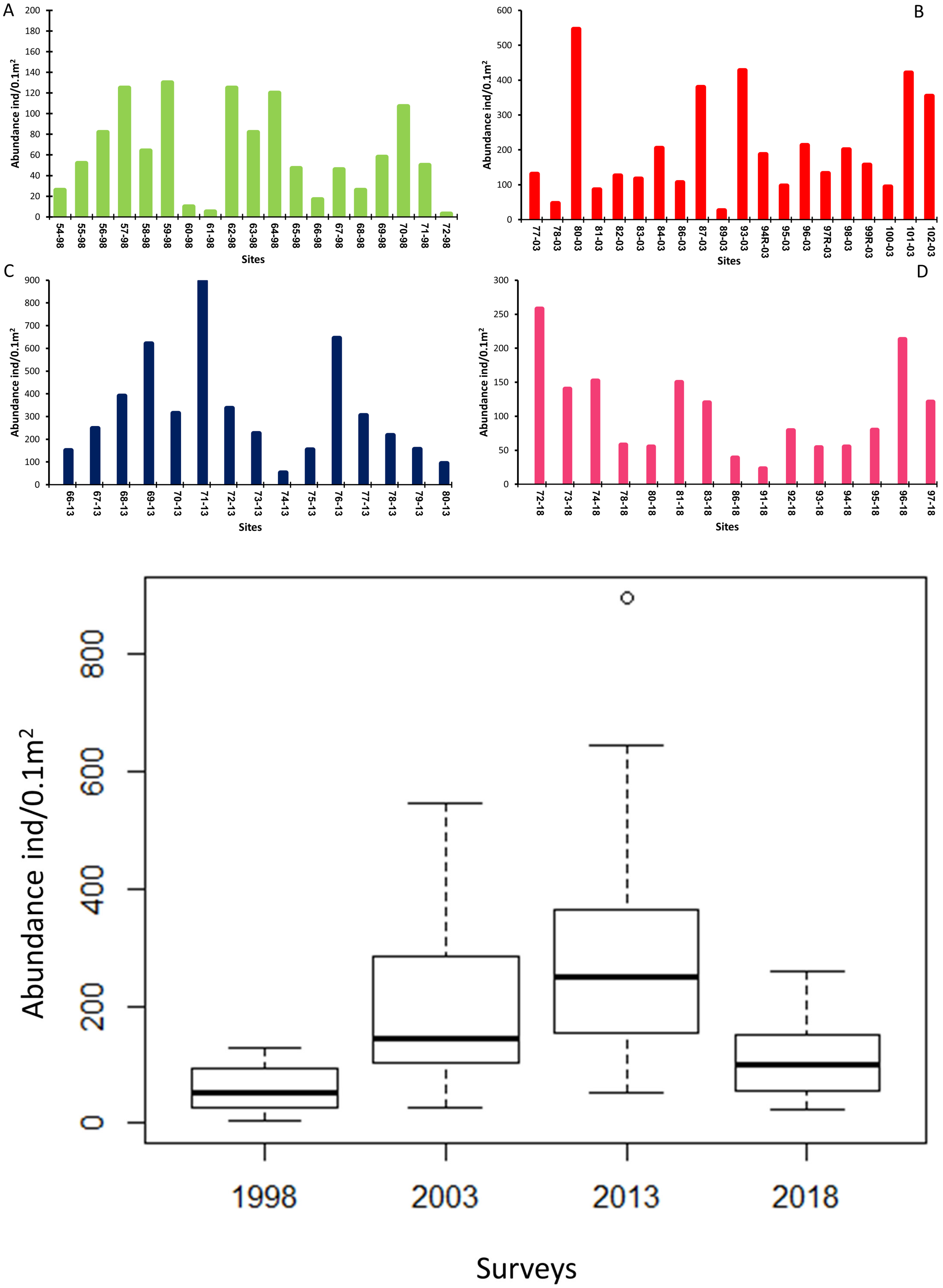

FIGURE 4a. Total abundance of polychaete families in Bahia de Todos Santos plotted across different sites and oceanographic surveys (A) 1998; (B) 2003; (C) 2013; (D) 2018. And **4b** Box plots show average polychaeta abundance and SD in the four sampling years

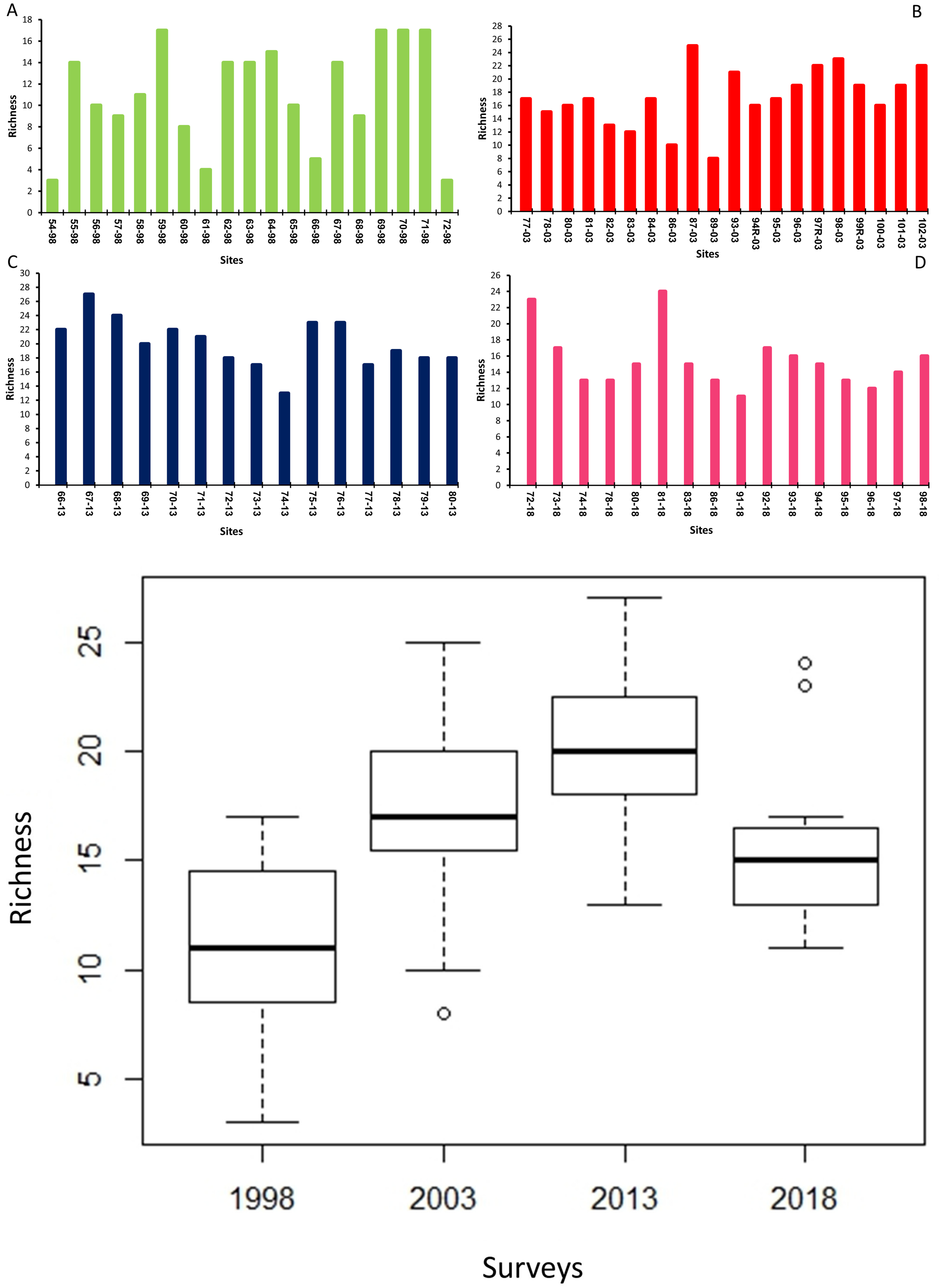

FIGURE 5a. Total richness of polychaete families in Bahia de Todos Santos plotted across different sites and oceanographic surveys (A) 1998; (B) 2003; (C) 2013; (D) 2018. And **5b** Box plots show average polychaeta richness and SD in the four sampling years.

The faunal groups that decreased their abundances compared 1998 were. Mollusca with 128 ind./0.1 m^2 (3.9%), and Echinodermata with 103 ind./0.1 m^2 (3%) (Fig. 3). The pattern indicated an increase in the proportion of polychaetes in 2013, and crustaceans and other invertebrates that dominated the community structure in 2018.

Benthic polychaete community characteristics of the sampled sites—The analysis of 70 stations in Bahia de Todos Santos through four oceanographic surveys (1998, 2003, 2013, 2018), resulted in a total of 11849 individuals belonging to the Class Polychaeta. An overall temporal trend in increasing polychaete abundance values was observed through 1998 (1175 ind./0.1 m^2); 2003 (4065 ind./0.1 m^2) and 2013 (4809 ind./0.1 m^2). The greatest increase in abundance was observed in 2013 with approximately four times the total organism compared to 1998. During the 2018 survey there was a decrease in abundance, 1805 ind./0.1 m^2 obtaining values similar to those in 1998 (Fig. 4a).

Family richness showed similar patterns during 2003 and 2013 with 37 families each, with a slight decrease in 1998 and 2018 where 34 and 33 families were identified respectively. Likewise, there was a temporal trend towards better spatial distribution in the number of families per station during 1998; 2003 and 2013. In 2013 there was a greater spatial homogeneity in the number of families per station (Fig. 6). In contrast, in 2018 there was greater spatial heterogeneity of families per station, although not as marked as that observed in 1998 (Fig. 5a). Of the 34 families identified in 1998, four accounted for 59% of the total number of individuals, these being Spionidae (26%), Maldanidae (13%), Ampharetidae (10%) and Cirratulidae (9%) (Fig. 6).

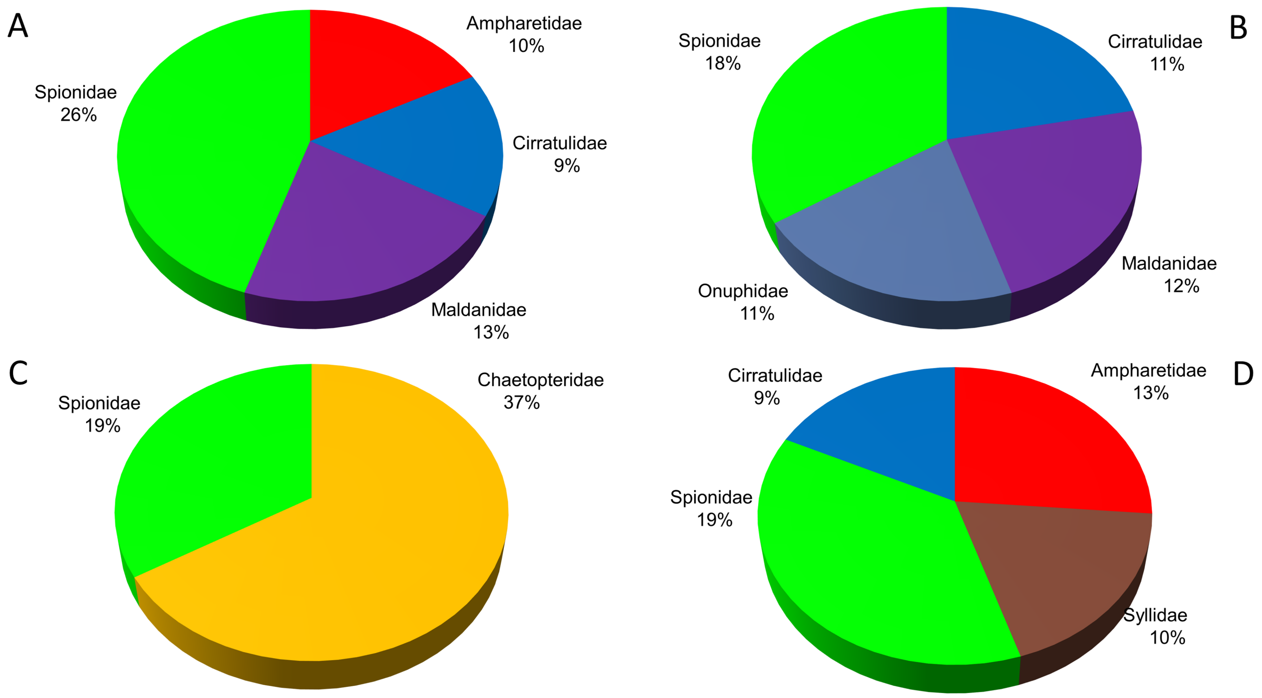

FIGURE 6. Percent composition of the most abundant polychaete families (>50% of the total abundance) in Bahia de Todos Santos across different sites and oceanographic surveys (A) 1998; (B) 2003; (C) 2013; (D) 2018. The remaining families are present in appendix I.

For 2003, 37 families were identified, of which four accounted for 53% of the total polychaete fauna, these were Spionidae (18%), Maldanidae (12%), Cirratulidae (12%) and Onuphidae (11%). During 2013, 37 families were identified, of which 2 represented 56% of the total abundance, these were Chaetopteridae (37%) and Spionidae (19%). For 2018, of the 33 identified families, four represented 51% of the total polychaetes and these families were Spionidae (19%), Ampharetidae (13%), Syllidae (10%) and Cirratulidae (9%) (Fig. 6). Polychaetes in the family Spionidae were best represented with 19% of the total abundance across surveys (1998–2018), except for 2013, were the Chaetopteridae were found most abundant with 37% of the total abundance.

Benthic polychaete communities -univariate ecological indices—Shannon-Winner index (H´) showed a spatial and temporal tendency to increase through the four oceanographic surveys (1998, 2003, 2013, 2018). These measured values fell into categories of ecological quality along the bay, high, medium, low, and very low values of diversity to indicate ecological status of an area.

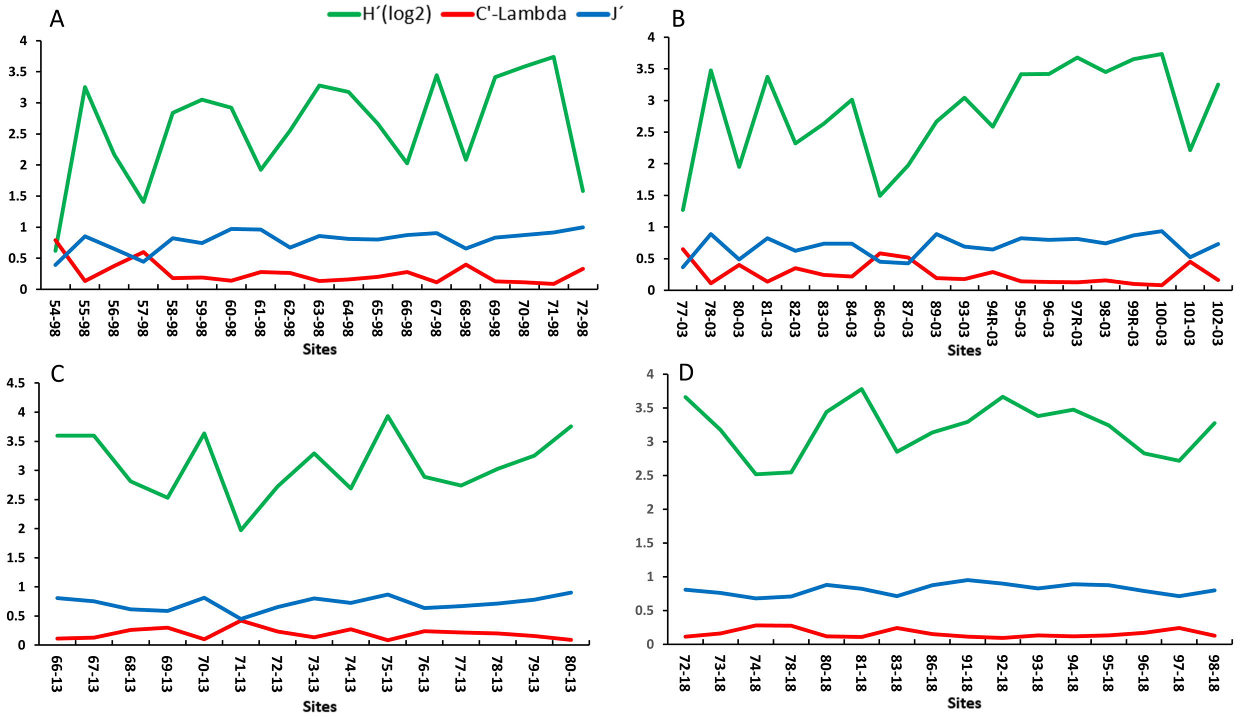

FIGURE 7. Relationship between diversity (H'), evenness (J') and dominance (C') of polychaete families in Bahia de Todos Santos across different sites and oceanographic surveys (A) 1998, (B) 2003, (C) 2013, and (D) 2018.

High diversity index values for 1998 (3.1–3.7); 2003 (3.0–3.7); 2013 (3.0–3.9) and 2018 (3.1–3.8) indicated an equitable distribution of abundance among families, and therefore were considered a heterogeneous community for the 42.1%; 55%; 53% and 68.75%, of the bay area across the survey years respectively (Fig. 7). Medium diversity index values in 1998 (2.0–2.9); 2003 (2.2–2.7); 2013 (2.5–2.8) and 2018 (2.5–2.9) indicate there was no equitable distribution of abundance among families, and were considered a moderately disturbed or stressed area for 36.8%; 25%; 40% and 31.25% of the bay area across the survey years respectively (Fig. 7). low diversity index values for 1998 (1.4–1.9); 2003 (1.3–1.9) and 2013 (1.98) indicate that the bay had a less equitable distribution of abundance among families, and the community tended towards homogeneity for 15.8%; 20% and 6.6% of the study area across the survey years respectively (Fig. 7). Very low diversity index values in 1998 (0.6) indicated that this area was a homogeneous community where the abundances of two families (Ampharetidae and Onuphidae) accounted for 5.3% of the bay (Fig. 7).

High Evenness values (J´) for 1998 (0.7–1.0); 2003 (0.8–0.9); 2013 (0.8–0.9) and 2018 (0.8–0.9), were considered to have a very good distribution of family richness for 73.68%; 40%; 33% and 62.5% of the bay area across survey years respectively (Fig. 7). Medium Evenness values (J´) for 1998 (0.65–0.67); 2003 (0.5–0.7); 2013 (0.58–0.78) and 2018 (0.68–0.78) were considered to have a good distribution of family richness for 21.05%; 40%; 60% and 37.5% of the bay area across survey years respectively (Fig. 7). Low Evenness values index (J´) for 1998 (0.39–0.44); 2003 (0.36–0.48) and 2013 (0.45) were considered to have a poor distribution of family richness for 5.27%; 20% and 6.6% of the bay area across survey years respectively (Fig. 7).

Benthic polychaete assemblages -multivariate analysis—The ordering graph resulting from non-Metric Multidimensional Scaling (n-MDS) analysis of similarity, based on the composition and abundance matrix of polychaete families, resulted in stress values for 1998 of 0.09; 2003 of 0.1; 2013 of 0.06, and for 2018 of 0.12 (Fig. 8). This indicated that the configuration obtained was a good representation of similar assemblages for polychaetes throughout the bay and through time. The n-MDS graph for 1998 shows a slight separation of a small group of stations (60, 66 and 68) located close to the zone where dredging sediments were deposited (Fig. 8A).

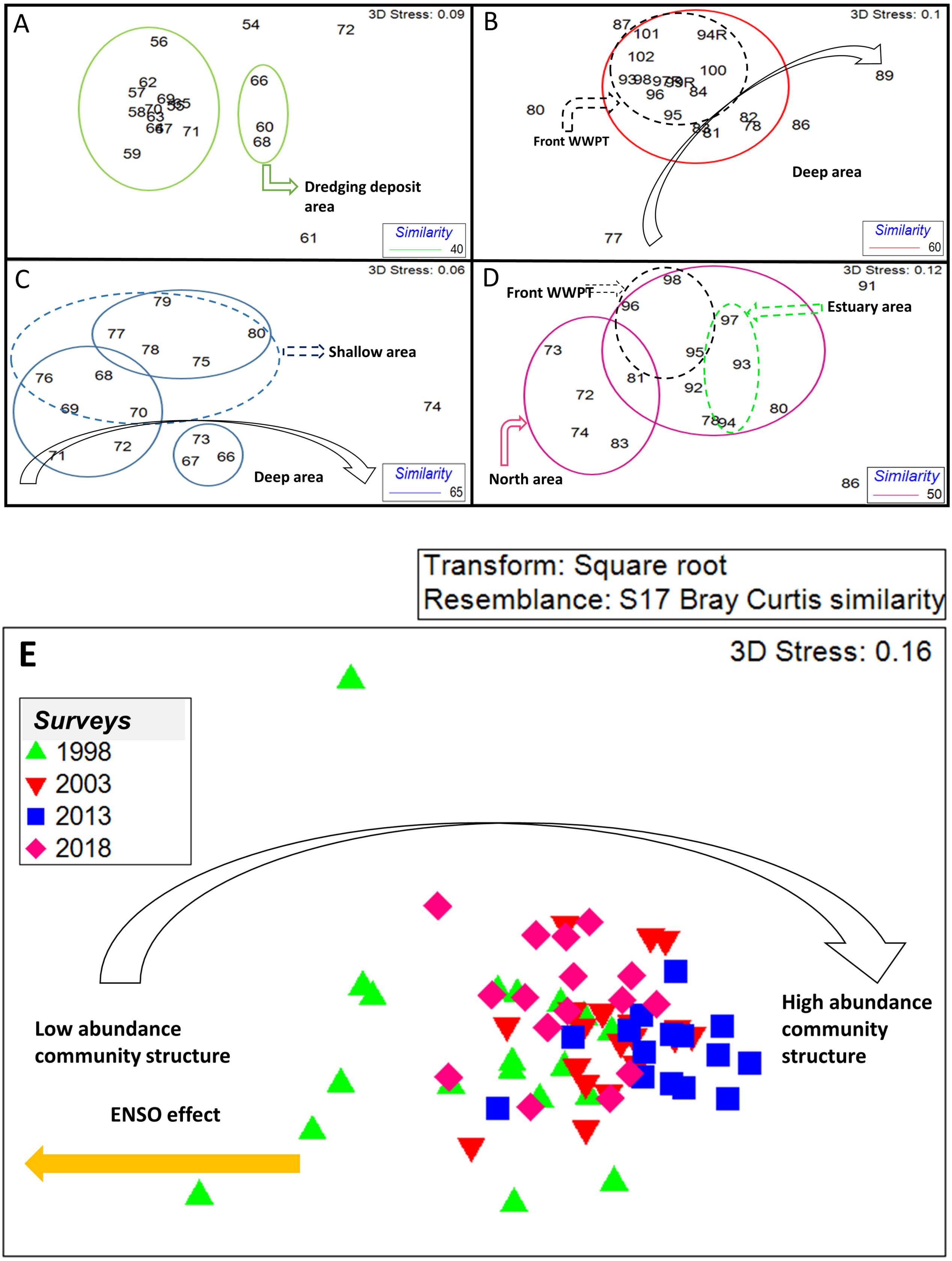

FIGURE 8. Two-dimensional non-metric multidimensional scaling ordination (nMDS) plot based on the Bray–Curtis similarity measure over the composition and abundance values of polychaete families in each oceanographic survey. (A) 1998; (B) 2003; (C) 2013; (D) 2018; and (E) comparison between of all oceanographic survey.

The n-MDS graph for 2003 showed, a separation of the stations (78, 81, 82, 83, 86, 89) located at the north entrance of the bay near Todos Santos Island and in the submarine canyon area (Fig. 8B). For 2013 n-MDS revealed a separation of the stations into two groups based on depth (shallow stations 68, 69, 70, 75, 76, 77, 78, 79, 80, and deep stations 66, 67, 71, 72, 73) (Fig. 8C). The n-MDS graph for 2018 showed a separation of stations influenced by the estuary area (91, 93, 94 and 97), and the wastewater treatment plants in the bay (95, 96 98) (Fig. 8D). Non metric multidimensional scaling generally showed changes in faunal associations found in 1998 compared to 2003 and 2013, and in 2018 a tendency to return to the same faunal associations observed in 1998 (Fig. 8E). This behavior was probably the effect of ENSO events that happened during the years 1997–1998 and 2016–2018 (Figure 8E).

SIMPER analysis found the similarity of the communities within oceanographic surveys (1998, 2003, 2013, 2018) to range from 33.04% to 47.92%. 2003 had the highest similarity values, and 2013 the lowest. During the 1998 survey, the two families that contributed most to the polychaete assemblages were Maldanidae (13.18%) and Spionidae (8.82%). For 2003 the families contributing the most were Syllidae (18.05%) and Terebellidae (11%). In 2013 the families Chaetopteridae (15.52%) and Cirratulidae (6.5%) contributed the most. In 2018 the families with the highest contribution were Spionidae (17.88%) and Cirratulidae (11.86%) (Table 2).

ANOSIM analysis revealed significant differences existed (P <0.001) between survey years in the structure of polychaete communities, except for the comparison between 1998 and 2018 (Table 3). This was mainly attributed to the temporal similarity in which the ENSO events have historically developed in the Pacific Ocean, because it is known that strong ENSO events developed during the 1997–1998 and 2016–2017 seasons which may have caused the abundance patterns to be similar in both 1998 and 2018.

TABLE 2. SIMPER analysis of family assemblages characterizing similarity for each of the groups formed through Bray-Curtis similarity and n-MDS plot through oceanographic surveys 1998–2018.

	Survey				
	1998			2003	
Families	Contribution %	Cummulative %	Families	Contribution %	Cummulative %
Maldanidae	13.18	13.18	Syllidae	18.05	18.05
Spionidae	8.82	22	Terebellidae	11.01	29.06
Nereididae	7.95	29.95	Onuphidae	10.63	39.69
Cirratulidae	7.30	37.25	Maldanidae	8.23	47.92
Lumbrineridae	6.95	44.20	Sigalionidae	7.97	55.89
Sigalionidae	5.84	50.04			
	Survey				
	2013			2018	
Families	Contribution %	Cummulative %	Families	Contribution %	Cummulative %
Chaetopteridae	15.52	15.52	Spionidae	17.88	17.88
Cirratulidae	6.50	22.02	Cirratulidae	11.86	29.74
Spionidae	5.62	27.64	Ampharetidae	11.75	41.49
Trichobranchidae	5.39	33.03	Sabellidae	6.84	48.33
Maldanidae	5.13	38.16	Lumbrineridae	6.69	55.02
Sigalionidae	5.01	43.17			
Ampharetidae	4.85	48.02			
Lumbrineridae	4.79	52.81			

TABLE 3. ANOSIM analysis result revealed significant differences existed (P <0.001) between survey years.

Groups comparison	R Statistic	Signifcance Level %
1998, 2003	0.270	0.1
1998, 2013	0.313	0.1
1998, 2018	0.108	0.8
2003, 2013	0.340	0.1
2003, 2018	0.376	0.1

Analysis of the relationship between benthic polychaete patterns with measured environmental parameters—The results of the Bio-Env analysis showed that there was a medium-low correlation between the environmental variables that best explain the changes in the distribution of polychaete families. The correlation coefficient values ranged from 0.392 to 0.573 (Table 4). During the 1998 and 2003 surveys two variables were recorded respectively, with percent organic carbon being a common variable, Cu was only reported for 1998 and depth during 2003. For 2013, the variable that best explained the changes in the distribution of polychaete families was Pb, which could be associated with changes in the structure of coastal sediments and the low flow of wastewater treatment plants.

TABLE 4. Bio-Env analysis result showed that there was a medium-low correlation between the environmental variables that best explain the changes in the distribution of polychaete families.

Survey	Correlation coeficient	Environmental factor
1998	0.392	CO% and Cu
2003	0.573	CO% and Depth
2013	0.572	Pb

Discussion

The present investigation represents the first effort focused on describing the temporal changes of polychaete communities along Bahia de Todos Santos, linking the analysis of composition, structure, and distribution of polychaete families and enviromental parameter measures.

Environmental Variables—Metals, sediment grain size and depth were the environmental parameters that had the greatest influence on polychaete communities in Bahia de Todos Santos. During 1998, the main environmental factors in the sediments were Cd (µg/g), Cu (µg/g), and Mn (µg/g), these were mainly recorded in deep areas, suggesting that these elements have a stratification tendency caused by depth, and possibly current circulation patterns along the bay. This same behavior was observed by Alvarez-Aguilar *et al.* (2017) during 2003 and 2013. Rodriguez-Villanueva *et al.* (2003), Argote-Espinoza *et al.* (1991), Ramirez-Alvarez (2000) and Macias-Zamora *et al.* (2016) mention that the oceanographic characteristics in Bahia de Todos Santos, combined with current patterns generate dispersion of chemical compounds that deposit in the sea-bed through along the coastline, and finally settle in deep areas. These factors along with the effect of heavy storms during ENSO events support the correspondence between depth, highest percentage of fine sediments and the accumulation of metals Cd (µg/g), Cu (µg/g), and Mn (µg/g) in the study area. Bryan & Langston (1992) and Rodriguez-Villanueva (2005) indicated that Cu (µg/g), and Mn (µg/g) are introduced and deposit by continental runoff and wastewater treatment plants and accumulate in coastal sediments. Frías-Espericueta *et al.* (2010) mentions that Cd is mostly associated with upwelling in the coastal zone, therefore it is common to find high concentrations of Cd in deep areas. The same behavior for Cd was recorded by Gutiérrez-Galindo *et al.* (2010) in areas near the submarine canyon adjacent to Todos Santos Islands. In general, we observed that during 1998, the sediment grain size and depth variables most influenced the dispersion of metals on a spatial scale (between-stations), and during 2003 and 2013 the depth variable had a greater influence on the performance of the other measured environmental variables, along with a decrease in trace metals concentrations possibly due to increasing droughts in the study area.

Macrobenthic patterns—The analysis of benthic macrofauna in Bahia de Todos Santos showed an increase in polychaetes of 13% between 1998 and 2018. Rodríguez-Villanueva *et al.* (2003) reported that polychaetes constituted 57% of total macrofauna. Previously in 1994, Rodriguez-Villanueva *et al.* (2000) indicated that polychaetes represented 61% of the benthic macrofauna. This could be a consequence of the strong ENSO events during 1997–1998, with high precipitation that introduced inputs of sediment from the coastline (Pavia & Badan 1998). Kuk-Dzul *et al.* (2012) indicated that composition, distribution and abundance of the benthic communities was related to the quality of their physical and chemical environment. Also, Zan *et al.* (2015) mentioned that natural environmental variables, such as sediment and hydrological conditions influence the structure of macrobenthic communities significantly.

Abundance patterns—Polychaete abundance doubled from 1998 to 2003, San Martin *et al.* (2000)

indicated that an altered area as a result of severe natural events undergoes recolonization processes. Pearson & Rosenberg (1978) note that polychaetes contain both sensitive and tolerant species, and they have been identified as a group that responds quickly to environmental disturbances or stress. Polychaete abundance continued to increase reaching its peak during the 2013 survey (4809 ind./0.1 m^2). Rodríguez-Villanueva *et al.* (2000) recorded in 1994 polychaete abundances of 4270 ind./0.1 m^2, after a weak ENSO event (1991–1992). It is worth mentioning that for 2018 a decrease in abundance was observed, with values very similar to those recorded during in 1998 by Rodríguez-Villanueva *et al.* (2003). Both years 1998 and 2018 were possibly affected or influenced by ENSO events of high magnitude. Jacox *et al.* (2016) indicated that these events had a similar magnitude and frequency causing abundant rainfall and generating high hydrographic energy in coastal areas. Gray (1974) and Gambi & Giangrande (1986) indicated that different characteristics of sediments usually reflect the circulation patterns of water bodies and in turn these sedimentary differences are a strong influence on the composition, abundance, and faunal diversity. During 2013, the highest number of organisms was observed, potentially signifying the overall effect of intense droughts during that time (Swain *et al.* 2014), where continental contributions such as wastewater, sediments and other pollutants from point and non-point source runoff to the coastal area were reduced. Alvarez-Aguilar *et al.* (2017) indicated that drought conditions caused less regional hydrodynamic perturbation in benthic environments and therefore favored an increased abundance and diversity of polychaetes.

Family patterns—The families best represented in the study area during 1998, 2003 and 2018 were Spionidae, Ampharetidae and Cirratulidae. These families are characterized as being indicators of environmental stress associated with areas of high organic matter (Bellan *et al.* 1988; Hale & Heltshe 2008; Ranasinghe *et al.* 2010), and previously were reported with high abundances in the study area by Rodriguez-Villanueva *et al.* (2000). The family Ampharetidae has been considered tolerant in high concentrations of Cu (Bryan & Gibbs 1987; Dean 2008), and this tolerance may explain the high abundance of these organisms registered for 2018 in areas near the wastewater treatment plants. During 2013 the families Chaeptoteridae and Spionidae were predominant, Alvarez-Aguilar *et al.* (2017) considered that they may be responding to accumulated organic matter and the stratification of coastal sediments.

Univariate measures—Lowest diversity index (H´) values were recorded during 1998, with the presence of homogeneous communities and a high proportion of families considered indicators of disturbed or stress sites found. Previously, Rodriguez-Villanueva *et al.* (2000) also recorded low diversity values in Bahia de Todos Santos for 1994. Fisher & Sheaves (2003) indicated that homogeneous sediments have few microhabitats and subsequently low numbers of species with one or few numerically dominant. On the other hand, during 2018 the highest proportion of stations with high diversity values (H´> 2) were obtained, registering heterogeneous communities favored by a habitat with ecological quality considered from good to very good. These changes between 1998 and 2018 may be associated with higher percentages of sands and low organic matter content due to high hydrodynamics in 2018. Fisher & Sheaves (2003) indicated that assemblages with low dominance are associated with heterogeneous sediments that allow a great variety of microhabitats that can be utilized.

Multivariate measures—The assemblages of polychaete families showed a pattern of response to the ENSO events (1997–1998 and 2016–2017), and the very strong drought of 2013–2014 which affected the distribution and composition of families throughout the area of study. The changes directly attributed to these climatic phenomena were mainly the modification of coastal sediments, as a consequence of the intensity and decrease of hydrographic energy in the area (Jacox *et al.* 2016; Mason & Goddard 2001; Minnich *et al.* 2000). Throughout the 1998–2013 surveys the families responsible for shaping the structure of communities were mostly organisms that feed on deposit matter on the surface such as spionids, ampharetids and cirratulids (Fauchald & Jumars 1979; Jumars *et al.* 2015). 2013 was characterized by an evident change in community assemblages, where chaeptoterids contributed a third of the abundance, and might be influenced by sediment stability due to low hydrodynamics as a consequence of drought conditions (Swain *et al.* 2014).

Environmental factors and community relationship—The correlation between environmental variables and polychaete families was medium-low, and is related to the hydrographic characteristics of the area attributable to the intensity of the ENSO events and strong drought periods that occurred during the span of the four oceanographic surveys. Rodríguez-Villanueva *et al.* (2003) determined that community patterns during the 1998 survey were mainly given by the sediment grain size and percent organic carbon, generated by the discharge from wastewater treatment plants. It was recorded for 2013 that Pb obtained a medium-high correlation. Frías-

Espericueta *et al.* (2010) indicated that the greatest contributions of Pb to aquatic environments came from atmospheric exchange and urban wastewater discharges. The 2013–2014 drought event favored low dispersion of Pb as a result of the sparse rainfall that occurred (Diaz & Wahl 2015; Griffin & Anchukaitis 2014). Alvarez-Aguilar *et al.* (2017) mentioned that this phenomenon allowed sediments to become more stable and that trace metals and organic compounds could accumulate more easily.

In conclusion, the coastal region in Northwest Mexico, has experienced rapid development and expansion of human population that will undoubtedly continue to increase stress over the bay system in Bahia de Todos Santos. Long-term spatial and temporal tracking of the sources of contamination and their effects on benthic communities can provide a useful tool for establishing baseline data that will allow resources managers to evaluate environmental conditions in the bay. With studies like this, future investigations can be developed at more specific levels to continue estimating the magnitude of environmental effects and distinguish between anthropogenic, and climatic shifts such as precipitation and drought events that play an important role in this area.

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APPENDIX I. Percent composition of polychaete families in Bahia de Todos Santos across different sites and oceanographic surveys.

Families	**Survey**			
	1998	2003	2013	2018
Ampharetidae	12.8	1.0	3.1	13.4
Amphinomidae	0.2	0.0	0.8	1.3
Capitellidae	1.1	11.7	1.7	1.3
Chaetopteridae	0.1	0.1	37.3	0.1
Cirratulidae	7.3	0.2	8.2	9.3
Cossuridae	10.9	0.1	0.9	0.2
Chrysopetalidae	0.1	0.0	0.0	0.0
Dorvilleidae	0.0	0.5	0.0	0.0
Eunicidae	0.2	1.2	0.1	0.5
Fauveliopsidae	0.0	0.2	0.0	0.0
Flabelligeridae	0.1	2.3	0.2	0.0
Glyceridae	0.4	0.2	1.0	0.8
Goniadidae	1.2	0.0	0.8	1.3
Hesionidae	0.2	2.8	0.0	0.1
Heterospionidae	0.0	0.0	0.0	0.0
Lumbrineridae	2.3	0.2	1.9	3.9
Magelonidae	1.2	12.5	1.0	5.2
Maldanidae	7.1	0.9	6.9	3.3
Nephtyidae	0.7	1.0	0.5	0.9
Nereididae	2.7	0.1	2.2	2.7
Oenonidae	0.4	11.1	0.1	0.3
Onuphidae	4.8	0.1	4.0	3.5
Opheliidae	0.0	1.5	0.1	0.3
Orbiniidae	1.9	7.0	0.4	0.8
Oweniidae	0.0	1.3	0.2	0.1
Paraonidae	1.6	0.0	1.0	2.5
Pectinariidae	0.1	0.0	0.2	0.9
Pholoidae	0.1	0.7	0.0	0.1
Phyllodocidae	0.9	0.0	1.4	2.9
Pilargidae	0.5	0.2	0.1	0.2
Pisionidae	0.0	0.1	0.0	0.0
Poecilochaetidae	0.0	0.0	0.1	0.6
Polynoidae	0.4	1.5	0.2	1.3
Sabellariidae	0.1	0.0	0.0	0.0
Sabellidae	4.9	0.0	1.1	7.0
Scalibregmatidae	0.0	3.9	0.1	0.5
Serpulidae	0.0	0.0	0.0	0.2
Sigalionidae	1.9	18.3	1.2	2.0
Spionidae	29.1	0.3	18.8	18.6
Sternaspidae	0.4	11.1	0.1	0.3
Syllidae	1.1	7.3	1.7	9.5
Terebellidae	2.4	0.2	1.5	4.2
Trichobranchidae	0.4	0.0	1.3	0.1