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Historical changes of sediments and mollusk assemblages in the Gulf of Batabanó (Caribbean Sea) in the twentieth century

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Abstract The first paleoecological reconstruction of the biogeochemical conditions of the Gulf of Batabanó, Caribbean Sea was performed from ^{210}Pb-dated sediment cores. Depth profiles of 20 major elements and trace metals, organic compounds, grain size, and mollusk assemblage composition were determined from 9 stations encompassing unconsolidated sediments in the gulf. Spatial heterogeneity was evident for the geochemistry of sediments and for the mollusk assemblage composition. Our reconstruction indicates that pollution is not a critical threat to the ecosystem, although a slight historical increase of lead enrichment factor was detected probably due to long-range atmospheric fallout. Mollusk assemblages were composed by 168 species belonging to 59 families and no temporal trends in the species diversity or assemblage composition were detected, suggesting no depletion of diversity or habitat loss. Other signals of habitat loss such as changes in organic budget or increase of fine sediment fraction were absent or weak. Nitrogen retained in sediments changed by <1% in the century, indicating no historical events of eutrophication or oligotrophication in the gulf. Historical decrease of fine sediment fraction in the eastern sector would be linked to modifications in sedimentation rate, land use, and/or particle transport from the shelf border; this also suggests that both sectors have different sedimentary dynamics. Although, on theoretical grounds,

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historical fishery may have caused deleterious ecosystem effects by overexploitation of spiny lobster stocks, no evidence of habitat degradation or loss, caused by fisheries, could be detected.

Keywords Geochronology · Mollusk · ^{210}Pb · Caribbean Sea · Ecosystem reconstruction

Introduction

The historical record of human activities is characterized by a steady increase of pressure on Earth's ecosystems (Haber 2007; WWF 2004). Facing this situation, the detection of historical trends in ecosystems (i.e., paleoecology) is an important aspect of environmental research to document human impacts, to identify main stressors, and to design proper strategies of mitigation and management (Willard and Cronin 2007). Data obtained from sediment cores provide insights into past conditions, the natural range of variability, and the ecosystem response to change (Brewster-Wingard and Ishman 1999). Paleoecology demands the use of temporal proxies like isotopes which allow the dating of the organisms and the conditions that occurred in the past; particularly, the analysis of biota is restricted to organisms with some kind of mineralized structures such as shells or valves.

The radionuclide ^{210}Pb has been widely used as a geochronometer of recent sediments in order to establish historical changes in decennial to secular time scales (e.g., Appleby 2008; Sanchez-Cabeza et al. 2000). The combination of dating with the analysis of the ecological structure of fossil assemblages is a powerful tool for disentangling historical processes. For instance, Brewster-Wingard and coworkers have performed a comprehensive study about the historical changes of the Everglade's ecosystem by integration of ^{210}Pb geochronology and analysis of pollen, mollusk, and ostracod assemblages (Brewster-Wingard and Ishman 1999; Wingard et al. 2004). They described the historical changes of biota distribution and environmental conditions and identified the hydrological regime as the main human-disturbed ecological process leading to habitat modification; further, they proposed sound actions for mitigation of impacts. In Cuba, geochronology using ^{210}Pb has been used to study sedimentary processes in two estuaries (Alonso-Hernández et al. 2006; Díaz-Asencio et al. 2009).

Mollusk assemblages, due to high diversity and long-standing calcareous shells, are a reliable taxonomic group for tracking historical changes in marine ecosystems (Brewster-Wingard and Ishman 1999; Gaiser et al. 2006). They have been successfully used in tropical and subtropical shallow waters to study historical changes such as salinity (Surge et al. 2003; Gaiser et al. 2006) and eutrophication (Ferguson 2008). Limitations of the use of mollusks as paleoproxies are shell fragmentation and time required for quantification. However, the coupling of presence/absence data and a reasonable knowledge of the species ecology and assemblages support reliable conclusions and inferences.

Human disturbances on ecosystems have steadily increased since the nineteenth century till the present. Therefore, changes in the structure and functioning of coastal ecosystems may have an important anthropogenic component. In this context, we address the Gulf of Batabanó, one of the best studied marine ecosystems in the Cuban Archipelago. The ecosystem includes five main types of marine benthic habitats (Cerdeira-Estrada et al. 2008) and is associated to mangroves in the landward border and coral reefs in the shelf border. Marine resources exploitation in the Gulf of Batabanó, the most productive area for coastal fisheries in the Cuban archipelago, includes lobsters, fishes, sponges, and mollusks.

The spiny lobster (*Panulirus argus*) is the most valuable fishery resource of the Cuban shelf and landings have consistently declined since 1990 (FAO-WECAFC 2007). Depletion could be explained on the basis of habitat deterioration/loss, overexploitation, decrease of primary productivity, or increased frequency of hurricanes and storms, but no conclusion has yet been reached. This problem has led to an increased interest in historical ecosystem trends; as a result, changes from the 1980s to 2000s in seagrass coverage and biomass of benthic invertebrates have been reported (Arias-Schreiber et al. 2008), but it is unclear if these changes belong to a longer temporal trend and the processes causing them.

A complete study of marine mollusk assemblages in the Gulf of Batabanó (Hoskins 1964) describes the structure and distribution of assemblages and relates them to the sedimentary environment. Hoskins (1964) divides the molluscan fauna in two main assemblages and concludes that granulometry, salinity, and presence of vegetation are the main ecological factors

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controlling the distribution of the mollusks. This allows comparing and validating historical reconstructions from sediment cores. Similarly, Martínez-Estalella and Alcolado (1990) study the ecological factors affecting the distribution and biodiversity of mollusks and conclude that this is determined by land influence, hydrodynamics, and presence of vegetation.

This work provides a quantitative description of the historical changes, during the last century, of the sedimentary environment and the mollusk assemblages of the Gulf of Batabanó. We present the first paleoecological study of this ecosystem to contribute to its proper management. The aims of this study are (1) to identify historical trends in both environment and mollusk assemblages in Gulf of Batabanó based on ^{210}Pb-dated sediment cores and (2) to suggest possible causes of the observed patterns in the context of natural/anthropogenic changes of the ecosystem.

Material and methods

Study area

Research was carried out in the Gulf of Batabanó, Caribbean Sea, on the southwestern shelf of Cuba Island (Fig. 1). The gulf is a shallow basin (mean depth of 6 m) with an approximate area of 20,000 km^2. The gulf land boundary is mostly covered by mangroves; human presence is reduced to several relatively small coastal settlements, but no big cities or industries. Subtidal habitats close to the coast are mostly classified as muddy with scarce vegetation (Cerdeira-Estrada et al. 2008). Seaward boundaries (i.e., Caribbean Sea) are constituted by coral reef ecosystems and the hydrodynamic regime is notably increased in the shelf border. The subtidal central area of the basin is mostly constituted by seagrass meadows of the spermatophyte *Thalassia testudinum* König (Cerdeira-Estrada et al. 2008). Other unconsolidated sediments conform to habitats such as bare sand, mud flats, and macroalgae beds. General circulation is from east to west, mainly originating from a branch of the Caribbean current. Salinity is close to that in the open sea (i.e., 32–35) and can decrease landward due to terrestrial runoff. The temperature shows a typical seasonal pattern with an annual range of 20–35°C.

Sampling

Sediment cores were collected from subtidal soft bottoms of the Gulf of Batabanó in November 2005 in nine sampling stations (Fig. 1). Sampling locations were restricted to areas of low hydrodynamic regime where physical disturbance and mixing of sediments should be at a minimum. The eastern part, with a stronger hydrodynamic regime, was, therefore, poorly covered. Surface sediments (<3 cm depth) were sampled from seven other stations using a stainless steel bucket and results are used as complementary information. Salinity and temperature were measured with a handheld probe YSI 30M and depth was measured with a diving barometer. During the sampling period, the abiotic factors were fairly constant (surface water temperature, 24–25°C; surface salinity, 32–33). Additional information on the sampling stations is provided in Table 1.

For geochronology, a single-sediment core was carefully collected at each station by scuba divers using a UWITEC system with plastic corer (1 m length, 8.6 cm inner diameter) and ensuring minimum disturbance of the water–sediment interface. The corer penetration ranged from 28 to 49 cm depth. Each core was sliced into 1-cm-thick sections till 10 cm depth, 2-cm sections till 20 cm depth, and 5-cm sections to the bottom. In the laboratory, sections were freeze-dried, homogenized, and stored in plastic vials for subsequent analysis. All manipulations were done with inert plastic materials in order to avoid metal contamination of the samples.

Mollusks

Samples were sieved through a 1-mm mesh; the retained material was observed under stereomicroscope and mollusk shells picked up. Mollusk species were identified based on the shell morphology. Species were reported as present when the shell was complete in more than two thirds and the umbo was intact.

Grain size

An aliquot of 1 g of dry sediment (<1 mm) was used to determine the sediment fraction smaller than 300 μm using the gravimetric method described by

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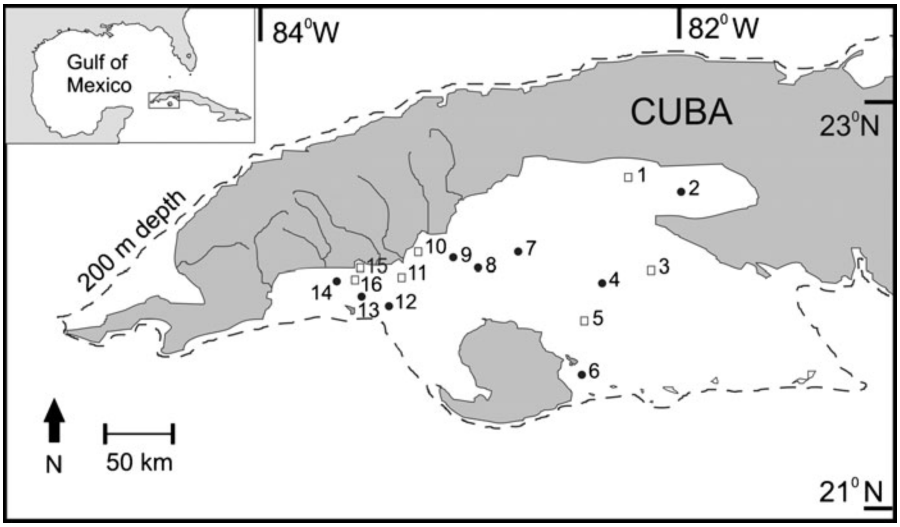

Fig. 1 Study area in the Gulf of Batabanó, Cuba. The *inset* shows the regional location of the study site. Sampling stations are indicated with *black circles* (cores for geochronology) and *open squares* (surface sediment). The proximate shelf boundaries are also shown

Bale and Kenny (2005). For determination of the grain size distribution of the finer fraction (<300 µm), an aliquot of 0.5 g of dry sediment was diluted with MilliQ water, 0.16 N NH_4OH was added as dispersant agent, and the solution was subjected to ultrasonication and passed through a laser beam-based system (MALVERN Mastersizer Micro v2.12).

Nutrients

The contents of total carbon and nitrogen were determined by using a CHN analyzer (Carlo Erba model 1602). Approximately 100–150 mg of dry sediment was encapsulated into a Sn foil cup and introduced into a combustion furnace. Organic carbon

Table 1 Characterization of the sampling stations in the Gulf of Batabanó

Station	Location	Core length (cm)	Water depth (m)	S	TN (%)	TC (%)	OC (%)	Number of species	Remarks on sediments
1	22°36.980 N, 82°13.020 W	–	5	28	0.2	12.3	2.1	26	Silty, no vegetation
2 (core)	22°34.390 N, 82°03.420 W	28	7	28	–	–	–	9	Silty, no vegetation
3	22°13.900 N, 82°13.730 W	–	5	34	0.1	12	1.5	14	Sandy, seagrass vegetation
4 (core)	22°06.000 N, 82°25.980 W	42	5	34	0.1	12.4	1.1	12	Sandy, seagrass vegetation
5	22°53.910 N, 82°27.925 W	–	7	35	0.1	12.2	1.3	13	Sandy, seagrass vegetation
6 (core)	21°41.420 N, 82°28.305 W	41	3	34	0.3	13.2	2.8	24	Close to mangroves, sulfide smell
7 (core)	22°12.450 N, 82°48.646 W	46	5	35	0.1	12.1	1.0	30	Sandy, seagrass vegetation
8 (core)	22°11.969 N, 83°01.806 W	49	7	34	0.2	12.5	1.9	11	Sandy, seagrass vegetation
9 (core)	22°15.299 N, 83°10.134 W	29	8	34	0.5	13.2	4.1	–	Silty, scarce vegetation
10	22°16.479 N, 83°15.951 W	–	3	34	0.5	11.6	4.3	26	Silty, no vegetation, sulfide smell
11	22°07.884 N, 83°22.313 W	–	8	34	0.2	5.1	1.3	30	Silty, no vegetation
12 (core)	22°04.593 N, 83°24.023 W	29	12	34	0.4	12.6	3.4	6	Silty, no vegetation, sulfide smell
13 (core)	22°06.530 N, 83°35.760 W	34	8	33	0.2	8.7	1.3	25	Silty, no vegetation, sulfide smell
14 (core)	22°09.360 N, 83°40.390 W	43	6	33	0.7	10.4	5.5	1	Silty, no vegetation, sulfide smell
15	22°10.920 N, 83°36.95 W	–	3	32	0.1	0.8	0.6	17	Silty, no vegetation, sulfide smell
16	22°13.399 N, 83°34.694 W	–	3	32	0.8	9.7	6.2	–	Silty, no vegetation, sulfide smell

Concentration of biogenic compounds and number of mollusk species refers to surface sediments (<3 cm). Stations where cores for geochronology were taken are indicated

S salinity, *TN* total nitrogen, *TC* total carbon, *OC* organic carbon, – no data

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was determined after treating the samples with concentrated HCl to remove inorganic carbon. Concentration of nutrients is expressed as the percentage of total dry weight.

Major and trace elements

Major and trace elements (Al, Si, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Zr, Mo, I, Cs, Ba, La, and Pb) were measured by energy dispersion X-ray fluorescence (XRF) spectrometry using a SPECTOR X-LAB PRO 2000 system. The system was calibrated for 4-g samples in sample cups with premounted 4-µm thick Prolene® thin film. Cups were filled with 4 g of dry and sieved (1 mm mesh size) sediment. The XRF analysis was performed by combining measurements with three different targets and enabled the determination of elements from atomic number 13 (Al) to 92 (U). In addition, International Atomic Energy Agency (IAEA) reference materials (IAEA-356, IAEA-405, and IAEA-433) were used to validate the measurements. Elemental concentration is expressed as absolute concentration in micrograms of an element in 1 g of dry weight.

Radionuclides and dating

^{210}Pb activity was determined by high-resolution alpha spectrometry of its decay product ^{210}Po, assumed to be at equilibrium. Aliquots (0.5 g) of dry sediment were spiked with ^{209}Po as a yield tracer and dissolved by adding a mixture of 1:1:0.5 HNO_3/HCl/HF using an analytical microwave system (Sanchez-Cabeza et al. 1998). ^{210}Po was electrodeposited onto silver disks and counted with an integrated Canberra alpha spectrometer with ion-implanted planar silicon (PIPS) detectors. The IAEA-384 reference material (Povinec et al. 2007) was used for data quality control.

Supported ^{210}Pb (=^{226}Ra) was calculated through ^{226}Ra in equilibrium. ^{226}Ra was analyzed by high-resolution gamma spectrometry with a low-background intrinsic Ge well detector (nominal efficiency, 60%; resolution, 2.1 keV at 1,333 keV). Samples were placed in sealed plastic containers and stored for at least 3 weeks in order to allow ^{226}Ra to reach equilibrium with its daughter nuclides. ^{226}Ra was determined via the 352-keV gamma rays emitted by its daughter nuclide ^{214}Pb in equilibrium. Efficiency calibration was performed using a Standard U-Ore (CANMET). The IAEA reference materials IAEA-313, IAEA-385 (Pham et al. 2008), and IAEA-384 (Povinec et al. 2007) were used to ensure data quality (Sanchez-Cabeza et al. 2008). Excess ^{210}Pb ($^{210}Pb_{ex}$) was calculated as $^{210}Pb_{ex}={}^{210}Pb-{}^{226}Ra$.

Sediment geochronologies were established with the ^{210}Pb dating model (Sanchez-Cabeza and Ruiz-Fernández 2011) and their detailed geochronology will be published elsewhere. The shallow depth of the cores combined with the high frequency of hurricanes in the region produces high surface mixing in the sediment, and consequently, constant activities of ^{210}Pb at the surface. Due to these specific conditions, we assume a homogeneous mixing process at the surface mixed layer (SML) and we applied the model constant flux and constant sedimentation (CFCS)$^{+SML}$ (Nittrouer et al. 1984; Boer et al. 2006). The model assumes that supply of ^{210}Pb to the seafloor is in steady state and that the SML coincides with the depth of steady-state or near-constant ^{210}Pb activity at the surface of the core. The model also assumes that the thickness of the SML has remained constant with time. The mean accumulation rates were determined with the CFCS model, and the age model was established with the constant flux model excluding the SML where present. ^{210}Pb radiochronologies were validated with the global fallout radionuclide ^{137}Cs. Apparent ^{210}Pb accumulation rates were also evaluated by comparing the measured maximum depth of ^{239,240}Pu penetration in two cores to the depth predicted by the apparent accumulation rate and thickness of the SML.

Data analysis

Univariate and multivariate techniques of data exploration and analysis were applied using Statistica 6.0® and PRIMER 6.1.6 (Clarke and Warwick 2001). No statistical tests could be done due to lack of replication because only one core was taken in each station. Each section of the core was considered as a sample for purposes of dating and graphical representation; however, we are aware that sections belonging to the same core are nonindependent from a statistical point of view. We partially overcome this by pooling data from several cores (stations) based on our knowledge of the spatial geomorphology of the gulf. Namely, correlations were performed independently on two groups of stations: eastern (2, 4, 6, 7, and 8) and western (9, 12, 13, and 14).

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Historical changes of abiotic data were analyzed by correlation-based principal component analysis (PCA). Relationships among samples were revealed on a scatter plot of the samples projected on the two first principal components (PC). For relevant variables, considered to be proxies of processes or phenomena, linear product–moment Pearson correlation was used to detect putative temporal trends; we consider reliable correlations those with a modular coefficient higher than 0.6 (i.e., explaining at least the 36% of the variance in the data). Enrichment factor (EF) was computed for lead, as a measure of the anthropogenic contribution versus the natural contribution (Díaz-Asencio et al. 2009). The EF was obtained by normalizing with Al using the equation: $EF = (Pb_s/Al_s)/(Pb_b/Al_b)$ where Pb and Al are the element concentrations and subscripts s and b refer to sample and background concentrations observed at the core bottom (noncontaminated), respectively.

For the analysis of mollusk assemblages, based on the presence/absence of species, a similarity matrix among samples was built using the Sorensen index. Further, a multidimensional scaling ordination (MDS) was performed to portray the similarity pattern among samples coded by station/section. Additionally, individual ordinations for each station were done to explore temporal changes in the assemblage composition. Afterwards, the similarity percentage (SIMPER) procedure (Clarke and Warwick 2001) was applied to multivariate data to identify the species that most contribute to the similarity among each station's samples; this species can be assumed to be characteristic of the stations where they appeared.

The number of species was calculated in each sample. In order to represent a functional aspect of the assemblage, each species was classified into three broad trophic guilds after morphology and behavior: suspension feeders, deposit feeders, and carnivores. All species belonging to the same trophic guild were summed and the occurrence frequency of each guild in each sample was calculated.

Results

Geochemical environment

Concentrations of 20 elements were recorded from the 9 cores (Supplementary data S1). As biogenic compounds (i.e., organic carbon, total carbon, and total nitrogen) were not measured in all sections, we looked for other variables as proxies of total nitrogen and organic carbon. The variable bromine (Br) concentration had a strong and significant correlation with total nitrogen ($r=0.86$, $n=39$, $p<0.05$) and with organic carbon ($r=0.83$, $n=39$, $p<0.05$); it was used as proxy of organic nitrogen and carbon compounds in the PCA.

The PCA indicates a clear spatial heterogeneity of the samples along the two gradients represented by the PC (Fig. 2a). Samples with the same label/station are clustered together independently of the section/year, indicating that, overall, the historical changes are overridden by spatial heterogeneity. Table 2 shows that PC1 represents a gradient of the mineral matrix of the sediment, with the larger modular coefficients associated to elements indicating marine (positive sign: $CaCO_3$) and terrestrial influence (negative sign: silicon, potassium, calcium, manganese, iron, rubidium, and barium). The projection of samples on PC1 suggests the existence of spatial differences in the mineral composition in the gulf. Stations in the western sector of the gulf (9, 12, 13, and 14) have a mineral composition with a larger land influence (i.e., more Si, Fe, and Al); on the other hand, samples from the eastern sector (2, 4, 6, 7, and 8) have a stronger marine component (more calcium).

PC2 represents a gradient in the organic component of the sediments (total nitrogen and carbon), as Br has the highest coefficient for this PC. There is also evidence of some spatial heterogeneity in the gulf regarding the sediment organic matrix: stations 2 and 9 have, respectively, the lowest and highest values in the putative gradient. PC3 was associated with the fine sediment fraction (<300 μm) and the trace elements Pb and Cr, suggesting a possible anthropogenic origin of these metals, mainly associated to the fine sediment particles (Table 2).

The temporal trends of PC1 and PC2 are shown in Fig. 2b, c, respectively. The temporal trends in the mineral matrix are not evident for each station in the scatter plot (Fig. 2b) and also the correlations between age and PC1 were relatively low (but significant) for both groups of stations (Table 3). We do not consider these temporal correlations robust enough; therefore, we suggest that there is no historical trend in the mineral matrix in the eastern and western sectors of the gulf. As observed in Fig. 2c, historical changes in

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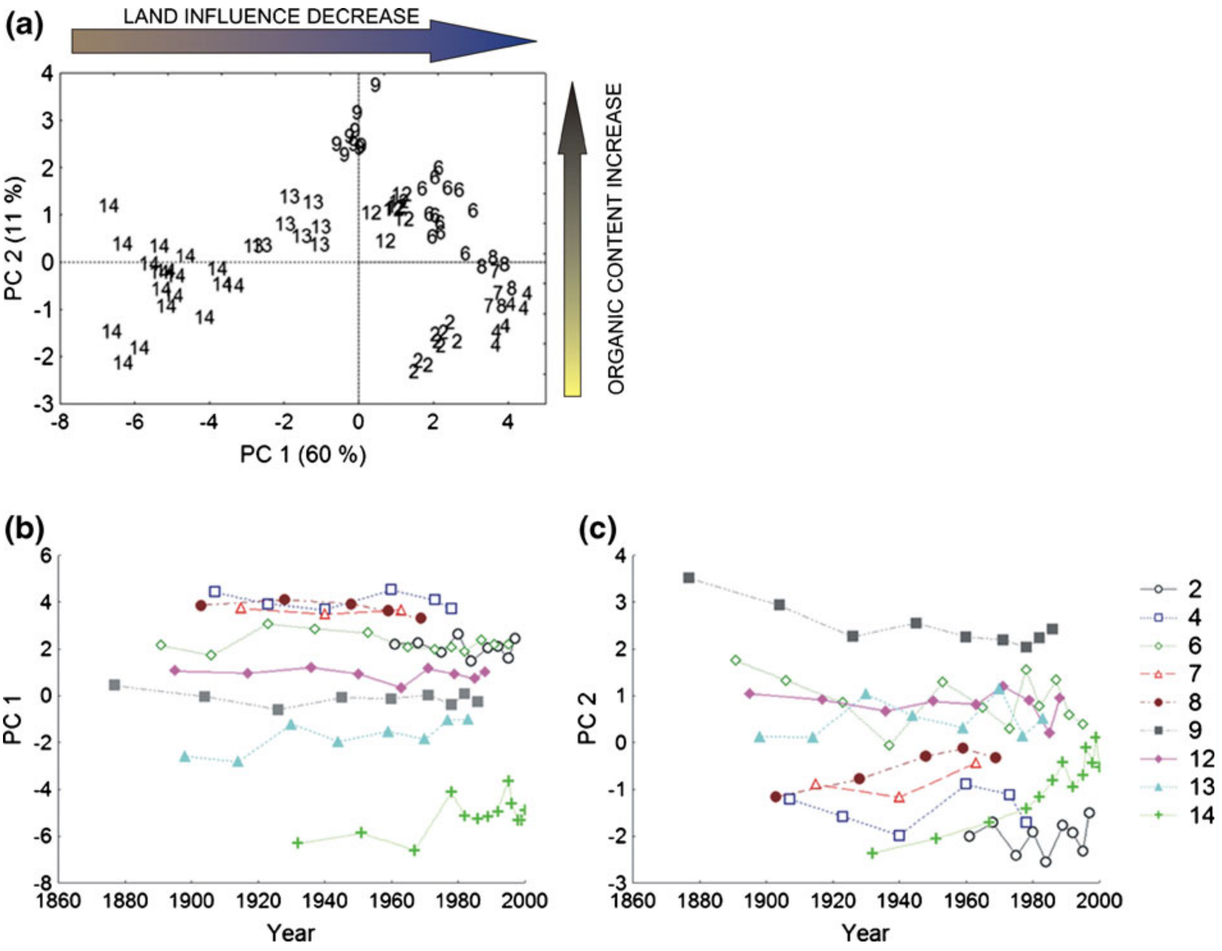

Fig. 2 **a** Ordination by correlation-based PCA of core sections. The ordination is based on 18 sedimentary variables. The fraction of explained variance by each component is shown in *parentheses*. *Arrows* suggest the interpretation of gradients on the axes: PC1 is a proxy for mineral composition and PC2 is a proxy for the organic component. **b**, **c** The temporal evolution of PC1 and PC2, respectively

the organic matrix were relatively more variable. Again, correlations fail to indicate a robust temporal trend of PC2. We concluded that there is not enough evidence of a consistent temporal change for the organic content in sediment (Table 3). Overall, we concluded that spatial trends (i.e., differences among stations) are more robust than historical ones.

We studied the temporal trends of the variables that we assume to be proxies for different processes/phenomena (Fig. 3): sediment particle size (percentage sediment<300 μm: Fig. 3a, b), composition of the mineral matrix (Si: Fig. 3c), nutrient concentration (total nitrogen: Fig. 3d), and chemical pollution (Pb EF: Fig. 3e, f). Particle size and Pb EF are plotted in two different graphs for clarity.

No clear spatial patterns (i.e., differences among stations) in the fine sediment contents can be inferred from Fig. 3a, b for individual stations. However, a temporal trend appears to exist, with a historical decrease of the sediment fine fraction in the eastern sector (Table 3 and Fig. 3a). This trend is robust for the eastern stations despite inclusion of station 2 in the correlation, which clearly shows an increase of the content of fine sediment; another correlation performed excluding station 2 resulted in a higher negative correlation ($r=-0.75$, $p<0.05$, $n=26$).

The changes in Si (Fig. 3c) indicate that stations close to land (13, 14, and to a lesser extent, 2, 9, and 12) show a higher content than stations in the central part of the gulf (4, 6, 7, and 8), suggesting that Si is

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Table 2 Coefficients making the eigenvectors in a PCA ordination of sediment samples from 9 stations based on 18 variables

Variable	PC 1 (60%)	PC 2 (11%)	PC 3 (8%)
Fraction< 300 μm	0.18	−0.02	*0.48*
Al	−0.78	−0.09	−0.004
Si	*−0.96*	−0.24	−0.07
S	−0.85	0.21	−0.04
Cl	−0.64	0.54	0.08
K	*−0.98*	−0.06	−0.004
Ca	*0.96*	0.07	0.03
Cr	−0.41	−0.11	*0.49*
Mn	*−0.92*	−0.04	−0.14
Fe	*−0.97*	−0.15	−0.05
Ga	−0.57	−0.53	0.27
Br	−0.42	*0.87*	0.07
Rb	*−0.96*	−0.04	0.11
Sr	0.88	0.04	0.37
I	−0.59	*0.68*	0.003
Ba	*−0.91*	−0.25	−0.04
Pb	−0.32	0.07	*0.83*
$CaCO_3$	*0.96*	0.07	0.03

The explained variance for each component is in parentheses. The highest coefficients for each PC are in italics

tracing terrestrial inputs to the sites. The silicon content is poorly (but statistically significant) correlated with sediment age in both sectors of the gulf (Table 3). Therefore, we cannot propose the presence of a reliable evidence of a historical change in the land influence, as Si is a tracer of terrigenous material. This lack of temporal trend is also present for other land trace elements such as iron, manganese, and aluminum (data not shown).

The magnitude of changes in total nitrogen is rather low (i.e., <1% dw sediment; Fig. 3d). The nitrogen temporal trends do not suggest a clear scenario of eutrophication or oligotrophication in the gulf as correlations are low and nonsignificant (Table 3). The other organic compounds (i.e., total and organic carbon) did not show any temporal trends either (graphs not shown) and they were correlated with total nitrogen.

The Pb concentration was below 10 μg g^{-1} dw at all stations, suggesting the absence of relevant chemical contamination. The Pb EF (using Al as normalizer) was calculated as an indicator of anthropogenic impact. The Pb EF was <2 for all sections (but one outlier), indicating no clear signal of contamination. Pb EF showed no clear historical trends, as revealed by correlations (Table 3).

Mollusk assemblages

A total of 168 species of mollusks belonging to 59 families, 17 orders, and 3 classes were recorded in the sediment cores (Supplementary data S2). A multivariate ordination of samples based on the presence/absence of species shows spatial changes in the

Table 3 Pearson correlation coefficients for seven sedimentary proxy variables versus age for two groups of stations: eastern (2, 4, 6, 7, and 8) and western (9, 12, 13, and 14)

Variable	Eastern stations (2, 4, 6, 7, and 8)	Western stations (9, 12, 13, and 14)
PC1	−0.46* (35)	−0.45* (44)
PC2	−0.22 (35)	−0.37* (44)
Percentage sediment<300 μm	−0.65* (35)	0.33* (44)
Silicon	0.50* (40)	0.39* (47)
Total nitrogen	−0.06 (14)	−0.16 (34)
Lead enrichment factor	0.01 (35)	−0.01 (47)
Number of species	0.42* (35)	−0.53* (44)
Percentage suspension feeders	−0.01 (35)	0.23 (44)

The number of observations is in brackets

PC principal component

*$p<0.05$, significant correlations

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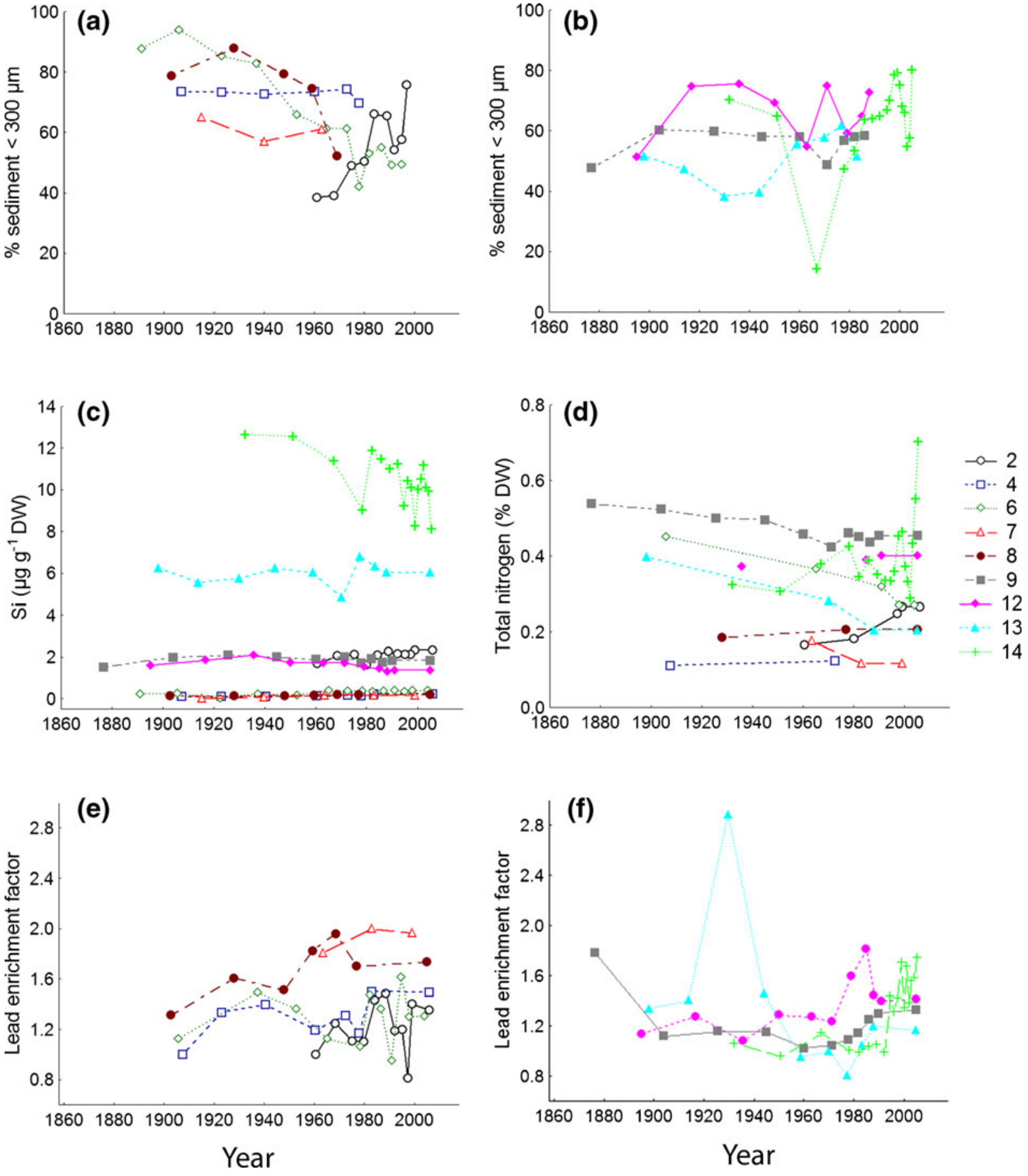

Fig. 3 Temporal evolution of selected sedimentary variables from sediment cores. **a**, **b** Percentage of sediment fraction >300 µm; **c** Si; **d** total nitrogen; **e**, **f** Pb EF. For the variables sediment fraction and Pb EF, the stations are divided into two groups (2–8 and 9–14) and depicted separately for better visualization

species composition of assemblages (Fig. 4). The relatively high number of samples and the high variance associated to their presence/absence cause a high level of stress in the ordination (0.24), indicating that the overall picture is reliable, but the details in the similarity between pairs of samples probably not. The

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overall picture suggests that stations 4, 7, and 8, located in the central part of the gulf, have a higher similarity in the assemblage composition. Stations located close to coastal areas (9, 12, 13, and 14) have a distinctive mollusk species composition because their samples are clustered together. Samples from stations 2 and 6 appear relatively far from other samples in the plot, suggesting a different composition of assemblages. In agreement with that observed for elemental composition, the pattern of clustering suggests that temporal changes are overridden by spatial ones, i.e., samples from the same stations are clustered together even if they belong to different years (sections).

Ordination of samples for each individual station does not suggest any historical trends in the assemblage composition (Fig. 5). The crossing of lines (i.e., temporal trajectories) indicates that there is no consistent temporal pattern of substitution of species in assemblages. The stations where more sections could be dated (e.g., 6 and 14) do not have any clear temporal tendency, thus reinforcing our initial conclusion.

We selected the mollusk species that most contribute to the similarity of samples belonging to the same station (i.e., all years pooled) using the SIMPER procedure (Table 4). The pattern of mollusk species presence suggests that some species are broadly distributed in the Gulf of Batabanó, and the most frequent were *Gouldia cerina*, *Crassinella lunulata*, *Antalis antillarum*, *Cylichnella bidentata*, and *Parvilucina* sp. Other species have more restricted spatial distribution, occurring only in one or two stations.

The historical trends in the univariate measurements of mollusk assemblages suggest that the number of species is higher and more variable in the stations close to the coastline compared to the other stations (Fig. 6a, b). For instance, the average number of species with all samples pooled for stations 9, 12, 13, and 14 was 30±14 species, while the average was 16±6 species for stations 2, 4, 6, 7, and 8. The historical trends in the number of species are rather weak, as suggested by the low correlation values (Table 3). Relatively large temporal fluctuations in the number of species exist (Fig. 6), but there is no evidence beyond doubt of a robust temporal change of the number of mollusk species in any of the two sectors of the Gulf of Batabanó.

Apparently, there is a differential spatial distribution of suspension feeder mollusks in both sectors of the gulf. The average percentage of suspension feeders to the mollusk assemblage has a higher contribution in the eastern sector (stations 2, 4, 7, and 8; station 6 was excluded because it clearly shows a different trend) with 57±16% compared with the western sector or stations closer to the coastline (35±9%). There were no significant historical changes in the fraction of suspension feeders for any of the two sectors in the gulf (Table 3). Average and variance of taxonomic distinctiveness indices were built based on the presence/absence of species, but they did not show any additional valuable information (data not shown).

The BIOENV procedure was used to match the multivariate patterns of species with a subset of combined abiotic factors. The combination of the

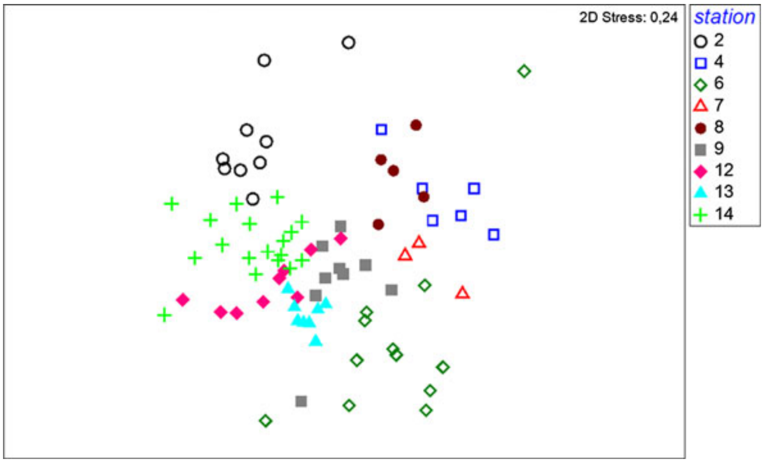

Fig. 4 MDS of samples based on the presence/absence of mollusk species from sediment core sections. Sample labels indicate the station/core

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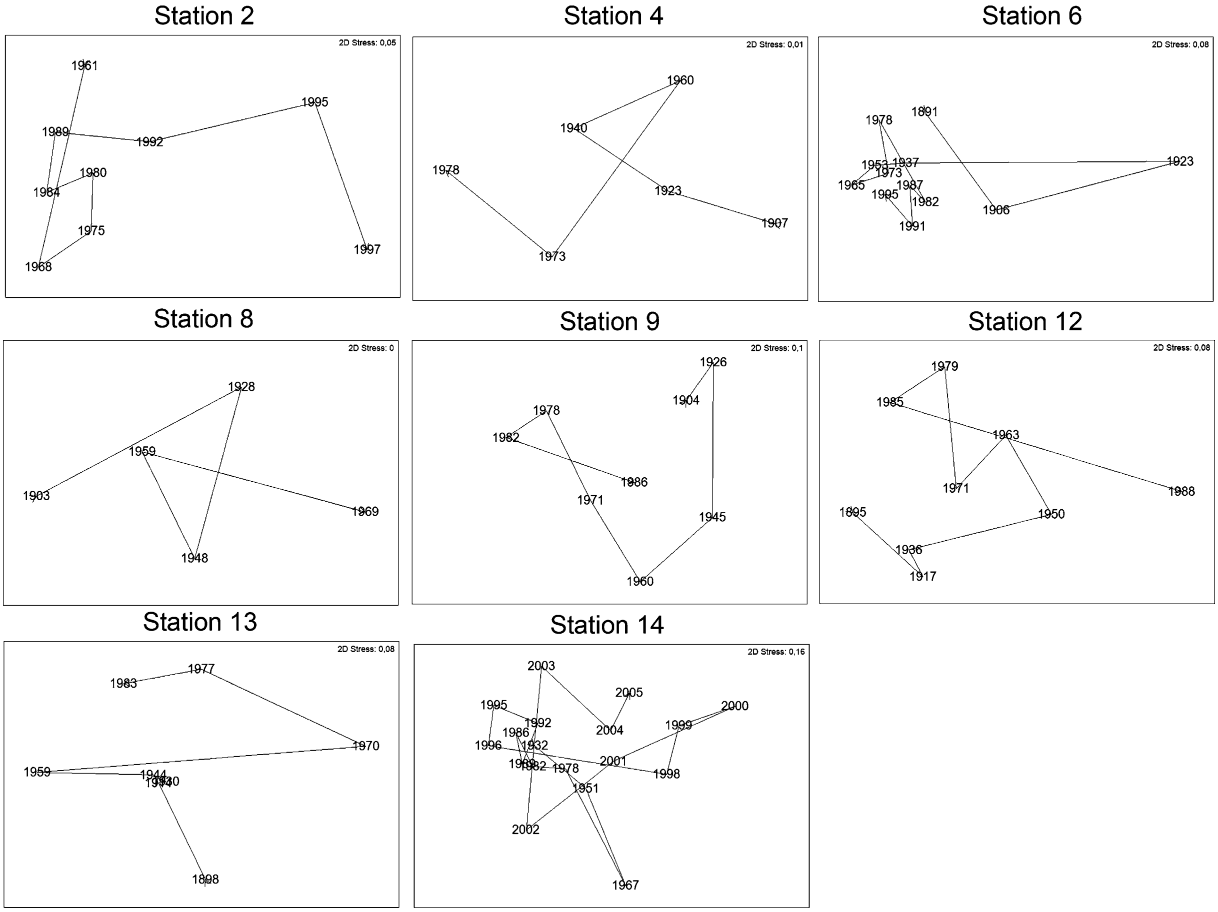

Fig. 5 MDS of samples for each station based on the presence/absence of mollusk species. Temporal evolution is shown by *lines* linking samples in the time sequence

elements Al, Cl, Br, and Pb had the best match with the multivariate structure of mollusk assemblages; however, this result should be used with caution since the correlation coefficient was low (0.32) though significant. Interestingly, the named combination of elements would represent different processes, i.e., the mineral matrix (Al), the organic fraction of sediments (Br), and the xenobiotics (Pb). This suggests that mollusk species have been influenced in some degree for all of these putative environmental drivers.

Discussion

We have reconstructed the geochemical and some biotic conditions of Gulf of Batabanó since 1880 from ^{210}Pb-dated sediment cores. Our paleodata cover a century and a large part of the subtidal unconsolidated bottom of the gulf including silty sediments, seagrass, and macrophyte beds. However, local spatial variability cannot be estimated due to lack of replication. Revisiting the objectives, we tried (1) to recover historical trends (or effects) in the Gulf of Batabanó and (2) to link them back to the causative disturbances. But very few of these causative links can be tested rigorously and often only indirect evidence for many of the processes can be retrieved. Based on our paleodata, we address historical changes in mollusk diversity, habitat loss, organic budget, pollution, and sediment composition.

The spatial heterogeneity of habitats and the relatively high diversity of mollusk assemblage hamper a general interpretation of historical changes in the Gulf of Batabanó. Multivariate methods are often more powerful to reveal trends than univariate/idiosyncratic (identity of particular species) methods

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Table 4 Mollusk species that most contribute to the similarity among samples from the same station (i.e., characteristic species)

Species	2	6	4	7	8	9	12	13	14
Finella adamsi	x								
Corbula caribaea[a]	x								
Antalis antillarum	x	x		x		x			
Lucina keenae	x								
Chione cancellata	x								
Tegula fasciata[a]		x							
Turbo castanea		x							
Eulithidium affinis		x							
Gouldia cerina			x	x	x		x		x
Crassinella lunulata[a]			x	x	x	x			x
Parvilucina sp.			x		x		x		
Zebina browniana			x						
Caecum pulchellum[a]				x					
Eulithidium bellum				x					
Pseudostomatella coccinea				x					
Trigonocardia guppyi					x				
Arcopsis adamsi[a]						x			
Anomalocardia auberiana[a]						x			x
Ganulina ovuliformis						x			
Mytilopsis leucophaeata						x			
Finella dubia							x		
Cylichnella bidentata							x	x	x
Acteocina candei								x	
Patelloida pustulata								x	
Pseudostomatella erythrocoma								x	
Gemma gemma									x

Cross indicates presence in the station

[a] Species considered by Hoskins (1964) to be characteristic of certain habitats within the Gulf of Batabanó

(Warwick and Clarke 1993), but in our study, the temporal trajectories based on multivariate assemblage composition did not show any interpretable pattern. Two issues considerably limit the detection and interpretation of ecological patterns: (1) the high number of mollusk species implies the presence of high redundancy and a considerable number of rare species with unclear distribution patterns and (2) data of presence/absence do not allow discerning between species with high biomass or density and rare species. The analysis and distribution of more frequent species previously described by Hoskins (1964) in the Gulf of Batabanó indicates that some of those reported as typical of particular habitats in the Gulf are nowadays more widely dispersed (e.g., *C. lunulata*), probably due to colonization.

Diversity depletion, as measured by species richness, is one of the main signals of habitat loss (Gaston and Spicer 2004). The study by Arias-Schreiber et al. (2008) recorded a reduction of the species diversity and seagrass coverage from the 1980s to 2004 in the western sector of the Gulf of Batabanó. We notice the existence of temporal fluctuations as large as 50% of total number of species in the western sector of the Gulf, but they do not follow a clear historical trend. For instance, fluctuation of species number in the first half of the century are the largest recorded in our study. Long-term changes in the seagrass meadow coverage can deplete the productivity (Dolbeth et al. 2011) and sediment retention capacity (Hemminga and Duarte 1999) of the ecosystem. Therefore, we analyzed other lines of evidence, namely, changes in the organic component of sediments, nitrogen budget, and fraction of fine sediment in sediment. None of these proxies showed consistent historical changes. Therefore, we do not have evidence supporting beyond doubt the existence of a historical diversity depletion or habitat loss in the Gulf of Batabanó.

Our evidence suggests that, in the time scale of a century, there is no relevant chemical pollution. Trace metal concentrations (e.g., copper, lead, and vanadium) are below the threshold values causing biological effects (Long et al. 1995). The Pb EF indicates only a slight enrichment in sediments, probably due to atmospheric fallout. Overall, trace metal contamination appears to be of little concern in the gulf (Alonso-Hernández et al. 2011). Although pollution close to small towns such as Coloma and Gerona has been reported (unpublished data), this appears to be a local phenomena.

The historical record of biogenic compounds suggests quite stable levels of carbon and nitrogen preserved in sediment. The range of change of total nitrogen in sediment is <1%, suggesting no clear signal of eutrophication or oligotrophication in the gulf. Oligotrophication of estuarine and coastal waters in the Cuban archipelago during the 1990s decade has been postulated by Baisre and Arboleya (2006) as response of the ecosystem to river damming by using the amount of water dammed as a proxy of nutrient retention in freshwater reservoirs. Our data, containing direct measurements of nitrogen in sediments along a century, do not support this event of oligotrophication.

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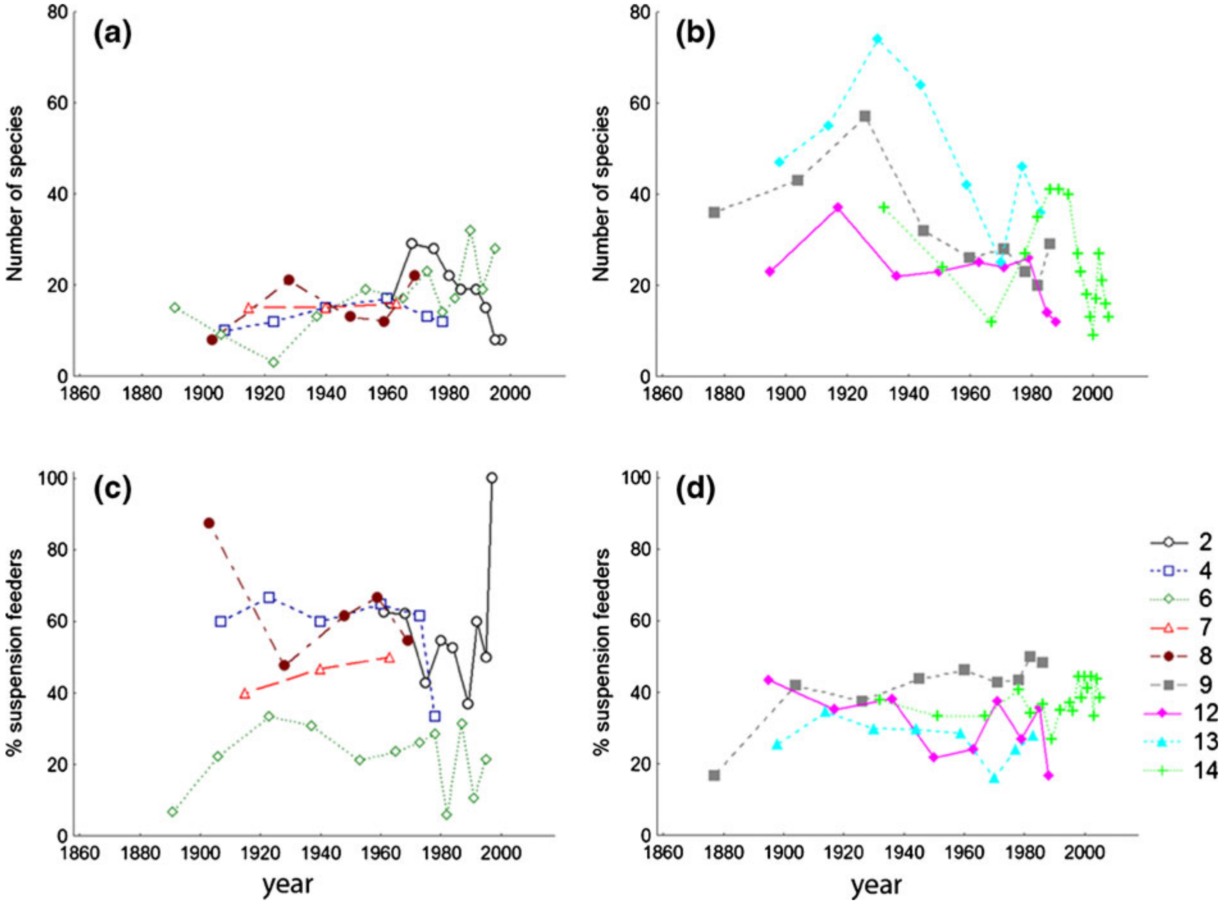

Fig. 6 **a**, **b** Temporal evolution of the number of species. **c**, **d** Temporal evolution of the fraction of suspension feeder mollusks. The stations are divided into two groups (2–8 and 9–14) and depicted separately for better visualization

Sediment composition in the gulf has a clear spatial heterogeneity, with stations in the eastern sector having stronger marine influence (higher relative content of $CaCO_3$) and stations in the western sections more influenced by land (higher relative content of Al, Si, and Fe). The historical diminution of the fine sediment fraction in the eastern sector of the gulf can be related with lower sedimentation rate due to lower terrigenous input and/or stronger particulate transport from the shelf border. Evidence of limited terrigenous input, probably due to changes in land use and constructions of dams and dikes, has been already reported (Alonso-Hernández et al. 2011). Thus, we can state that historical changes have occurred regarding sediment composition and that the western and eastern sectors have different dynamics of sediments.

Paleoecological data of Caribbean fisheries indicate that the fishing effort became a threat to the structure of the marine ecosystems at least since 1950 (Baisre 2010; Fitzpatrick 2010). The consistent depletion of the spiny lobster landings (FAO-WECAFC 2007) provides evidence of overexploitation of this fishery resource in the Gulf of Batabanó. Overfishing causes the deterioration of coastal ecosystems (Jackson et al. 2001), but we could not detect clear signals of habitat degradation in the gulf. Conversely, we have no conclusive evidence to assert that depletion of fisheries is linked to historical changes in the habitat quality in the Gulf of Batabanó.

Conclusion

Our reconstruction indicates that pollution is not a critical threat to the ecosystem. Biological data and organic and nutrient budgets do not support the

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existence of events of diversity loss, habitat degradation, or oligotrophication in the ecosystem. Historical decrease of fine sediment fraction in the eastern sector would be linked to modifications in the sedimentary regime, land use, and/or particle transport from the shelf border. No evidence of habitat degradation could be detected, so the deleterious effects of fisheries on the ecosystem cannot be supported by our data, nor the assertion that depletion of fisheries are caused by habitat loss.

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References

Alonso-Hernández, C. M., Diaz-Asencio, M., Munoz-Caravaca, A., Delfanti, R., Papucci, C., Ferretti, O., et al. (2006). Recent changes in sedimentation regime in Cienfuegos Bay, Cuba, as inferred from ^{210}Pb and ^{137}Cs vertical profiles. *Continental Shelf Research, 26*(2), 153–167.

Alonso-Hernández, C. M., Conte, F., Misic, C., Barsanti, M., Gómez-Batista, M., Díaz-Asencio, M., et al. (2011). An overview of the Gulf of Batabanó (Cuba): Environmental features as revealed by surface sediment characterisation. *Continental Shelf Research, 31*(7–8), 749–757.

Appleby, P. G. (2008). Three decades of dating recent sediments by fallout radionuclides: A review. *The Holocene, 18*(1), 83–93.

Arias-Schreiber, M., Wolff, M., Cano, M., Martínez-Daranas, B., Marcos, Z., Hidalgo, G., et al. (2008). Changes in benthic assemblages of the Gulf of Batabanó (Cuba)—Results from cruises undertaken during 1981–85 and 2003–04. *Pan-American Journal of Aquatic Sciences, 3*(1), 49–60.

Baisre, J. (2010). Setting a baseline for Caribbean fisheries. *Journal of Island & Coastal Archaeology, 5*(1), 120–147.

Baisre, J., & Arboleya, Z. (2006). Going against the flow: Effects of river damming in Cuban fisheries. *Fisheries Research, 81*(2–3), 283–292.

Bale, A. J., & Kenny, A. J. (2005). Sediment analysis and seabed characterization. In A. Eleftheriou & A. D. McIntyre (Eds.), *Methods for the study of marine benthos* (pp. 43–86). Oxford: Blackwell.

Boer, W., van den Bergh, G. D., de Haas, H., de Stigter, H. C., Gieles, R., & van Weering, C. E. (2006). Validation of accumulation rates in Teluk Banten (Indonesia) from commonly applied ^{210}Pb models, using the 1883 Krakatau tephra as time marker. *Marine Geology, 227*(3–4), 263–277.

Brewster-Wingard, G. L., & Ishman, S. E. (1999). Historical trends in salinity and substrate in Central Florida Bay: A paleoecological reconstruction using modern analogue data. *Estuaries, 22*(2), 369–383.

Cerdeira-Estrada, S., Lorenzo-Sánchez, S., Areces-Mallea, A., & Martínez-Bayón, C. (2008). Mapping of the spatial distribution of benthic habitats in the Gulf of Batabanó using Landsat-7 images. *Ciencias Marinas, 34*(2), 213–222.

Clarke, K. R., & Warwick, R. M. (2001). *Change in marine communities: An approach to statistical analysis and interpretation* (2nd ed.). Plymouth: PrimerE Ltd.

Díaz-Asencio, M., Alonso-Hernández, C. M., Bolanos-Álvarez, Y., Gómez-Batista, M., Pinto, V., Morabito, R., et al. (2009). One century sedimentary record of Hg and Pb pollution in the Sagua estuary (Cuba) derived from ^{210}Pb and ^{137}Cs chronology. *Marine Pollution Bulletin, 59*(4–7), 108–115.

Dolbeth, M., Cardoso, P. G., Grilo, T. F., Bordalo, M. D., Raffaelli, D., & Pardal, M. A. (2011). Long-term changes in the production by estuarine macrobenthos affected by multiple stressors. *Estuarine, Coastal and Shelf Science, 92*(1), 10–18.

FAO-WECAFC. (2007). *Report of the Fifth Regional Workshop on the Assessment and Management of the Caribbean Spiny Lobster. FAO Fisheries Report, 826*. Rome: FAO Western Central Atlantic Fishery Commission.

Ferguson, C. A. (2008). Nutrient pollution and the molluscan death record: Use of mollusc shells to diagnose environmental change. *Journal of Coastal Research, 24*(supplement 1), 250–259.

Fitzpatrick, S. M. (2010). Viewing the sea from the reefs. Comment and forum synthesis on Julio Baisre's "Setting a Baseline for Caribbean Fisheries". *Journal of Island & Coastal Archaeology, 5*(1), 173–178.

Gaiser, E. E., Zafiris, A., Ruiz, P. L., Tobias, F. A. C., & Ross, M. S. (2006). Tracking rates of ecotone migration due to salt-water encroachment using fossil mollusks in coastal South Florida. *Hydrobiologia, 569*(1), 237–257.

Gaston, K. J., & Spicer, J. I. (2004). *Biodiversity: An introduction* (2nd ed.). Oxford: Blackwell.

Haber, W. (2007). Energy, food, and land—The ecological traps of humankind. *Environmental Science and Pollution Research, 14*(6), 359–365.

Hemminga, M. A., & Duarte, C. M. (1999). *Seagrass ecology*. Cambridge: Cambridge University Press.

Hoskins, C. W. (1964). Molluscan biofacies in calcareous sediments, Gulf of Batabano, Cuba. *Bulletin of the American Association of Petroleum Geologists, 48*(10), 1680–1704.

Jackson, J. B. C., Kirby, M. X., Berger, W. H., Bjorndal, K. A., Botsford, L. W., Bourque, B. J., et al. (2001). Historical overfishing and the recent collapse of coastal ecosystems. *Science, 293*(5530), 629–638.

Long, E. R., MacDonald, D. D., Smith, S. L., & Calder, F. D. (1995). Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. *Environmental Management, 19*(1), 81–97.

Martínez-Estalella, N., & Alcolado, P. M. (1990). Características generales de las comunidades de moluscos de la macrolaguna del Golfo de Batabanó. In P. M. Alcolado (Ed.), *El bentos de la macrolaguna del Golfo de Batabanó*. Habana: Editorial Academia.

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Nittrouer, C. A., DeMaster, D. J., Mckee, B. A., & Cutshall, N. H. (1984). The effect of sediment mixing on ^{210}Pb accumulation rates for the Washington continental shelf. *Marine Geology, 54*(3–4), 201–221.

Pham, M. K., Sanchez-Cabeza, J. A., Povinec, P. P., Andor, K., Arnold, D., Benmansour, M., et al. (2008). A new certified reference material for radionuclides in Irish Sea sediment (IAEA-385). *Applied Radiation and Isotopes, 66*(11), 1711–1717.

Povinec, P. P., Pham, M. K., Sanchez-Cabeza, J. A., Barci-Funel, G., Bojanowski, R., Boshkova, T., et al. (2007). Reference material for radionuclides in sediment IAEA-384 (Fangataufa Lagoon sediment). *Journal of Radioanalytical and Nuclear Chemistry, 273*(2), 383–393.

Sanchez-Cabeza, J. A., & Ruiz-Fernández, A. C. (2011). ^{210}Pb sediment radiochronology: an integrated formulation and classification of dating models. *Geochimica et Cosmochimica Acta*. doi:10.1016/j.gca.2010.12.024.

Sanchez-Cabeza, J. A., Masqué, P., & Ani-Ragolta, I. (1998). ^{210}Pb and ^{210}Po analysis in sediments and soils by microwave acid digestion. *Journal of Radioanalytical and Nuclear Chemistry, 227*(1–2), 19–22.

Sanchez-Cabeza, J. A., Ani-Ragolta, I., & Masque, P. (2000). Some considerations of the ^{210}Pb constant rate of supply (CRS) dating model. *Limnology and Oceanography, 45* (4), 990–995.

Sanchez-Cabeza, J. A., Pham, M. K., & Povinec, P. (2008). IAEA Programme on the quality of marine radioactivity data. *Journal of Environmental Radioactivity, 99*(10), 1680–1686.

Surge, D. M., Lohmann, K. C., & Goodfriend, G. A. (2003). Reconstructing estuarine conditions: oyster shells as recorders of environmental change, Southwest Florida. *Estuarine, Coastal and Shelf Science, 57*(5–6), 737–756.

Warwick, R. M., & Clarke, K. R. (1993). Increased variability as a symptom of stress in marine communities. *Journal of Experimental Marine Biology and Ecology, 172*(1–2), 215–226.

Willard, D. A., & Cronin, T. M. (2007). Paleoecology and ecosystem restoration: Case studies from Chesapeake Bay and the Florida Everglades. *Frontiers in Ecology and the Environment, 5*(9), 491–498.

Wingard, G. L., Cronin, T. M., Holmes, C. W., Willard, D. A., Dwyer, G., Ishman, S. E., et al. (2004). Ecosystem history of southern and central Biscayne Bay: Summary report on sediment core analyses – Year two. U.S. Geological Survey Open File Report 2004, 1312.

WWF—World Wide Fund for Nature. (2004). *Living planet report*. Cambridge: Banson Productions.