Functional organization of the benthic macrofauna in the Bizerte lagoon (SW Mediterranean Sea), semi-enclosed area subject to strong environmental/anthropogenic variations

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Abstract: The Bizerte lagoon belongs to a large lagoonal complex increasingly affected by anthropogenic activities during the last years. At the same time, it is influenced by seawater inputs and by the freshwaters coming from Ichkeul Lake and several wadis, this giving rise to greatly fluctuating environmental conditions. To study the functional organization of the benthic macroinvertebrates, 11 stations facing the main important contamination sources were sampled using a 0.1 m² Van Veen grab. Our results showed that the ecosystem presented signs of trophic imbalance and the overall macrobenthic community was very impoverished, despite the apparent satisfactory ecological status showed by biotic indices. In this situation, microbial food web replaced the herbivore one while only some invertebrate species tolerant to environmental fluctuations were able to survive in such conditions.

Résumé : Organisation fonctionnelle de la macrofaune benthique dans la lagune de Bizerte (SW Méditerranée), milieu semi-fermé soumis à de fortes variations environnementales et anthropiques. La lagune de Bizerte appartient à un grand complexe lagunaire de plus en plus touché par les activités anthropiques ces dernières années. Dans le même temps, elle est influencée par les apports d’eau de mer et par les eaux douces en provenance du lac Ichkeul et de plusieurs oueds. Ceci induit de fortes fluctuations des facteurs environnementaux. Pour étudier l’organisation fonctionnelle de la macrofaune benthique, 11 stations en face des principales sources de contamination ont été échantillonnées à l’aide d’une benne Van Veen (0,1 m²). Nos résultats montrent que l’écosystème présente des signes de déséquilibre trophique et la communauté macrobenthique est très appauvrie, malgré le bon état écologique apparent montré par les indices biotiques. Dans cette situation, la boucle microbienne a remplacé le réseau trophique herbivore et seulement quelques espèces d’invertébrés tolérant les fluctuations de l’environnement ont pu survivre dans de telles conditions.

Keywords: Bizerte lagoon ● Benthic macrofauna ● Functional organization ● Trophic structure ● Biotic indices ● Environmental status

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Introduction

By their situation at the land-sea interface, coastal waters are ecologically very important and remarkably productive, but very fragile essentially in transitional locations subject to environmental/anthropogenic constraints (Mouillot et al., 2005; Rossi et al., 2006; Blanchet et al., 2008). Thus, rely only on physico-chemical approaches to study the impact of pollution in these complex areas can be confusing. However, the joint use of both biological and physico-chemical approaches is the efficient way to understand the functioning of the ecosystem and to distinguish the predominant factors (Carvalho et al., 2006; Puente et al., 2008). Several univariate biotic indices are developed for the assessment of environmental quality of coastal-transitional locations, and some of them are used in the context of the European Water Framework Directive (Dauvin et al., 2007). If the majority of these biotic indices are efficient in coastal areas, they are, however, less efficient in transitional waters where stressors are more important and, often, extreme conditions can play an important role in the community structure (Mouillot et al., 2005; Afli et al., 2008). Thus, in these transitional areas, biotic indices must be more improved, adapted and intercalibrated (Borja & Dauer, 2008).

Studying benthic fauna can detect real ecological impact of stressors at the community and ecosystem levels in coastal and transitional areas (Fano et al., 2003), because this community is consisted of sedentary invertebrates, exhibiting different tolerances to stress and having relatively long life-spans which allows it to reflect the water/sediment quality conditions (Dauer, 1993; Borja et al., 2000; Salas et al., 2004).

The Mediterranean region is of sub-wet shade climate, where the summer is hot and dry and the winter is cool and rainy. These characteristics and some other regional specificities, such as the fluctuations of floods, temperature and salinity give some peculiarities to the biodiversity in Mediterranean lagoons (Danovaro et al., 2000; Mistri et al., 2000; Rossi et al., 2006). The study site, the Bizerte lagoon (Fig. 1), is a remarkable Mediterranean ecosystem because it is in front of many natural/anthropogenic constrains. In winter, winds and rain are strong, so that waters coming from a large catchment basin and the Ichkeul Lake via several wadis are mixed and freshwater flow is very important (Soussi, 1981). The water temperature measured in Bizerte lagoon at approximately 10 cm below the surface varies from 11.5 to 29.5°C (Béjaoui et al., 2008). In summer, marine influence is higher than in the other seasons, and the effect of high temperatures induces stratification of the water column (Sakka Hlaili et al., 2003). Consequently, seasonal gradients of salinity in Bizerte lagoon may be relatively high ranging, on average, from 20 in winter to 40 in summer (Harzallah, 2003). In addition, the Bizerte lagoon ecosystem is currently destabilized by the worn water rejections coming from the bordering cities (Dellali et al., 2001). The population around the lagoon in 2004 was 163,000 inhabitants, about 70% in Bizerte town. Other important towns bordering the lagoon are Menzel Bourguiba, with a naval port and a metallurgic factory, Menzel Abderrahman and Menzel Jemil. Some other industries (iron and steel plant, cement factory, refinery) are established on its shoreline (Essid & Aissa, 2002). Moreover, the construction of dams in upstream Ichkeul Lake affected its natural equilibrium, causing a reduction of freshwater supply from about 165 to only 20 million m³ per year (Harzallah, 2003).

In this work, we tried to study the functional organization of the benthic macrofauna relying on the trophic structure and biotic/biodiversity indices. Then we tried, where possible, to identify key environmental factors that govern the functioning of the lagoon by using univariate/multivariate statistical analysis.

Material and Methods

Sampling and laboratory procedures

The water-sediment interface and bottom sediments were sampled in 11 stations, situated near sewage locations (Fig.1). The surveys were carried out in December 2001 on...
board a research vessel. Water samples were taken by diving and sediment samples were collected with a 0.1 m² Van Veen grab according to Borja et al. (2000) and Rosenberg et al. (2004). The minimum sampling surface required was estimated to be three samples with such grab according to Borja et al. (2000), Rosenberg et al. (2004) and Gόmez Gesteira & Daunin (2005). Thus, four samples were collected at each station, three to study fauna, which were fixed in a 7% formaldehyde/seawater solution and one to analyse the sediment characteristics. Part of collected sediments was immediately frozen in the dark to measure organic matter and chlorophyll \(a\) contents. The remaining sediments were used to analyse the granulometry. Salinity, \(pH\), temperature and dissolved oxygen (DO) were measured \textit{in situ} with a multiparameter WTW 340i. The water concentration of phosphates, nitrites and nitrates were measured according to Strickland & Pearsons (1965).

Fauna samples were sorted out through a 1 mm mesh sieve and the invertebrates were preserved in 70% alcohol prior being identified to the lowest possible taxonomic level. The granulometry was analysed after drying during 48 hours at 60°C, then washing through a 63 μm, drying again at 60°C and sieving through an AFNOR (French

<table>
<thead>
<tr>
<th>Biotic index</th>
<th>Algorithms</th>
<th>Index value</th>
<th>Site pollution Classification</th>
<th>Ecological status</th>
</tr>
</thead>
<tbody>
<tr>
<td>I2EC</td>
<td>(EG_1 &gt; 40, 20 &lt; EG_3 &lt; 40) and (EG_4 &lt; 20)</td>
<td>0</td>
<td>Unpolluted</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>(20 &lt; EG_1 &lt; 40, EG_3 &gt; 40) and (EG_4 &lt; 20)</td>
<td>2</td>
<td>Slightly polluted</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>(EG_1 &lt; 20, 20 &lt; EG_2 &lt; 40) and (EG_3 &gt; 40)</td>
<td>4</td>
<td>Meanly polluted</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>(EG_1 &lt; 20, 20 &lt; EG_3 &lt; 40) and (EG_3 &gt; 40)</td>
<td>6</td>
<td>Heavily polluted</td>
<td>Poor</td>
</tr>
<tr>
<td></td>
<td>Azoic</td>
<td>7</td>
<td>Extremely polluted</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(D) very low / presence of (EG_1, EG_2) and (EG_3)</td>
<td>1</td>
<td>Slightly polluted</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>(D) very low / presence of (EG_2, EG_3) and (EG_4)</td>
<td>3</td>
<td>Meanly polluted</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>(D) very low / presence of (EG_2, EG_3) and (EG_5)</td>
<td>5</td>
<td>Heavily polluted</td>
<td>Poor</td>
</tr>
<tr>
<td>AMBI</td>
<td>(0.0 - \frac{EG_1 + 1.5 \times EG_2 + 3 \times EG_3 + 4 \times EG_4 + 6 \times EG_5}{100})</td>
<td>0.0-1.2</td>
<td>Unpolluted</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.2-3.3</td>
<td>Slightly polluted</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.3-4.3</td>
<td>Meanly polluted</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.3-5.5</td>
<td>Heavily polluted</td>
<td>Poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.5-7.0</td>
<td>Extremely polluted</td>
<td>Bad</td>
</tr>
<tr>
<td>BENTIX</td>
<td>(6 \times GS + 2 \times GT) where (GS = EG_1 + EG_2) and (GT = EG_3 + EG_4 + EG_5)</td>
<td>4.5-6.0</td>
<td>Pristine</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.5-4.5</td>
<td>Slightly polluted</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5-3.5</td>
<td>Moderately polluted</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0-2.5</td>
<td>Heavily polluted</td>
<td>Poor</td>
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<tr>
<td></td>
<td></td>
<td>0</td>
<td>Azoic</td>
<td>Bad</td>
</tr>
<tr>
<td>(H')</td>
<td>(-\sum \frac{n_i}{N} \log_2 \left( \frac{n_i}{N} \right))</td>
<td>(&gt; 4)</td>
<td>Unpolluted</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3-4</td>
<td>Slightly polluted</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2-3</td>
<td>Meanly polluted</td>
<td>Moderate</td>
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<td></td>
<td></td>
<td>1-2</td>
<td>Heavily polluted</td>
<td>Poor</td>
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<tr>
<td></td>
<td></td>
<td>(&lt; 1)</td>
<td>Extremely polluted</td>
<td>Bad</td>
</tr>
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</table>
Association of Standardization) succession meshes. The granulometric structure was then estimated as the percentage (in weight) of each sediment fraction (Buchanan, 1971). Chlorophyll a (Chl.a) was measured fluorimetrically (Lorenzen & Jeffrey, 1980), total hydrocarbons (TH) according to Danovaro et al. (1995) and total organic matter (TOM) by ignition at 450°C for 6 hours (Fabiano & Danovaro, 1994). Heavy metal contents (Zn, Cu, Fe, Mn, Ni and Pb) were estimated after digesting the sediment in aqua regia (HCl-HNO₃-H₂O) at 95°C, and analysing them by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) and Mass Spectrometry (ICP-MS) (Yoshida et al., 2002).

Data analysis

Sediments were classified using the Shepard’s diagram (Shepard, 1954) and their respective types were determined according to Chassé & Glémarec (1976). The relationships between mud contents and concentrations of the main sediment pollutants were estimated by linear regression analyses using the Pearson product-moment correlation coefficient. The principal fauna synthetic parameters; density (D), specific richness (S), Shannon-Wiener index (H’) and evenness or equitability (J) were estimated for each station.

The assessment of the environmental quality was made possible by using three biotic indices based on the ecological groups (Table 1), I2EC (Grall & Glémarec, 2005), AMBI (Borja et al., 2000) and BENTIX (Simboura et al., 2006). All these indices qualify the ecological status within a five-class scale of pollution and possible by using three biotic indices based on the ecological groups (Table 1), I2EC (Grall & Glémarec, 2005), AMBI (Borja et al., 2000) and BENTIX (Simboura et al., 2006). All these indices qualify the ecological status within a five-class scale of pollution and

- Ecological group 1 (EG1): species sensitive to organic enrichment (initial status). They include the specialist carnivores and suspension feeders, which disappear in polluted areas
- Ecological group 2 (EG2): species indifferent to organic matter enrichment (from initial to slight unbalance), which include necrophagous scavengers
- Ecological group 3 (EG3): tolerant species (slight unbalanced situations), which are favoured by organic matter enrichment (essentially selective deposit feeders)
- Ecological group 4 (EG4): second-order opportunistic species (slight to pronounced unbalanced situations), which are mainly non selective deposit feeders predominant in polluted areas
- Ecological group 5 (EG5): first-order opportunistic species (pronounced unbalanced situations), which are some deposit feeders developing well in very polluted areas.

All species were classified into trophic groups according to Fauchald & Jumars (1979) and notably modified by Grall & Glémarec (1997), Afli & Glémarec (2000) and Pranovi et al. (2000):
- Herbivores (H): algae-feeding organisms (e.g. some echnids)
- Necrophagous (N): feed on carrions deposited on the bottom (essentially gastropods and decapods)
- Detritus feeders (DF): feed on particulate organic matter, essentially vegetable detritus (mainly amphipods and tanaids)
- Carnivores (C): predatory animals (mobile polychaetes, sea-anemones)
- Micrograzers (µG): feed on benthic microalgae, bacteria and detritus (essentially polyclaphores and gastropods)
- Suspension-feeders (SF): feed on suspended food in the water column (e.g. most bivalves)
- Selective deposit-feeders (SDF): feed on organic particles which settle on the sediment (most sedentary polychaetes)
- Non selective deposit-feeders (NSDF): burrowers which ingest the sediment from which they take their food.

To distinguish the possible major factors structuring the trophic chain, a Correspondence Analysis with Canonical Standardization (CCA) was established with the Statistica software on the values of the Bray-Curtis similarity after square-root transformation between trophic groups and main physico-chemical parameters (Bray & Curtis, 1957; McArdle & Anderson, 2001; Anderson & Willis, 2003). This data transformation aims to link trophic groups to physico-chemical parameters measured at the sampled stations (Duggal, 1999; Somerfield, 2008).

Results

In total, 49 macro-invertebrate species, of which more than 60% are polychaetes, were identified at the sampled stations. But, molluscs are more important in term of density (60%) followed by polychaetes (28%) and crustaceans (12%). High specific abundances are registered respectively for Actinia sp. (203 ind.m⁻² at B3), Dosinia lupinus (Linnaeus, 1758) (180 ind.m⁻² at B4), Nephtys spp. (176 ind.m⁻² at B11), Tellina tenuis da Costa, 1778 (170 ind.m⁻² at B4), Cymodoce truncata Leach, 1814 (103 ind.m⁻² at B3), and Nereis diversicolor (O.F. Müller, 1776) (70 ind.m⁻² at B4). However, Eunice pennata (O.F. Müller, 1776) and Pagurus sp. have the wider spatial distribution...
since they are present at respectively 64% and 55% of the sampled stations.

Synthetic fauna parameters (Fig. 2) show some differences between sampled stations. They are very low at some stations, such as B10 and B11 where respectively only 2 and 4 species were identified. Density varies from 10 (B10) to 470 ind.m\(^{-2}\) (B3), specific richness from 2 (B10) to 17 species (B6) and evenness from 0.15 (B1) to 0.52 (B8). The analysis of the trophic structure (Table 2) show that stations B3, B2, B11, B6, B8 and B7 are dominated by carnivores (C) (77% on average), B4, B5 and B1 are co-dominated by deposit feeders (SDF and NSDF) (44%) and suspension-feeders (SF) (47%) and B9 shows equivalent proportions of suspension feeders, deposit feeders and carnivores. Nevertheless, the very low specific richness and density at B10 prevent us from discussing the trophic balance.

The sediment tends to be fine in all sampling stations basically muds, sandy muds and fine sands (Fig. 3). Mud contents are significantly correlated (p < 0.05) with total organic matter, total organic carbon, Ni, Fe, Cu and Pb and not with total hydrocarbons, chlorophyll \(a\) and Zn and Mn (Fig. 4). Heavy metals contents (Fe, Zn, Cu, Mn and Pb) are clearly higher in front of the Menzel Bourguiba metallurgic factory (B3). On the other hand, dissolved oxygen (Table 3) is lower in the ship canal (B9 and B10) and in the sea (B11) and relatively higher in the west of the lagoon (B6 and B7). However, temperature, salinity and pH show no clear difference between the stations, except perhaps at B11 where temperature is slightly higher and salinity and pH are
Figure 4. The Pearson correlation coefficient (r) between mud content and main physico-chemical parameters measured in the sediment. Ni: nickel, Cu: copper, Fe: iron, Pb: lead, Zn: zinc, Mn: manganese and Chl a: chlorophyll a. Marked correlations (r*) are significant at $p < 0.05$.

Figure 4. Coefficient de corrélation de Pearson (r) entre le taux de vase et les principaux paramètres physico-chimiques mesurés dans le sédiment. Ni : nickel, Cu : cuivre, Fe : fer, Pb : plomb, Zn : zinc, Mn : manganèse et Chl a : chlorophylle a. Les corrélations marquées (r*) sont significatives à $p < 0.05$. 
slightly lower. Phosphate contents are higher in the ship canal (B9), nitrites facing wadis Halima/Soula (B1) and in the sea (B11) and nitrates facing wadi Tinja (B2) and Menzel Abderrahman (B8) and in the ship canal (B10).

On the other hand, only the two first axes of the CCA carried out on trophic groups and physico-chemical parameters (Total Inertia = 0.082, Chi² = 276.7, df = 96, p < 0.001) were considered (Fig. 5). Their cumulative eigenvalues represent more than 90% of which more than 81% are ensured by the 1st axis alone. Three groups can be identified by this analysis. The first (group 1) which is clearly separated from the two others is consisted of µG and N-P nutrients (PO₄, NO₂ and NO₃). All these variables have higher contributions to inertia (respectively 44.3%, 13.1%, 13.2% and 19.5% on axis 1) (Table 4). The second group (group 2) is located in the middle of the graphic and is consisted of the trophic groups DF, NSDF and N, organic matter (TOC, TOM, Chl. a), DO, pH and Cu. But only one trophic group (DF) has high contributions (17.1% on axis 1).
and 71.6% on axis 2). As for TH which have high contributions (14.2% on axis 1 and 42.5% on axis 2), there are completely separated from the other variables, and the nearest trophic group is DF. In fact, the high value of concentration of TH is registered at the only station (B3) where DF are present (15%). However the third group (group 3), the only group located in the negative values of the first axis, is consisted of the trophic groups SDF, SF and C, heavy metals Ni, Pb, Zn, Mn and Fe, M and S. But only C have a high contribution (15.7% on axis 1).

The three biotic indices based on ecological groups (I2EC, AMBI and BENTIX) classify all stations to be in a high-good ecological status, except B2/B7 which are classified by I2EC as ecotones 3/5 corresponding to meanly/heavily pollution (Fig. 6). However, $H'$ classifies B6, B8, B7 and B9 to be in a high-good ecological status, B3 and B2 to be in a moderate ecological status and the other stations to be in a poor ecological status.

### Discussion

**Community structure**

Macrobenthic community in the Bizerte lagoon seems to be biologically poor. For example B10 and B11 count respectively only 2 species (Dentalium dentalis Linnaeus, 1758 and Cucumaria sp.) and 4 species (Armandia polyophthalma Kukenthal, 1887, Caulleriella alata (Southern, 1914), Nephtys hombergii Savigny in Lamarck, 1818 and Nephtys sp.). These locations are subjected to the urban inputs of the Bizerte town extended on both sides from the ship canal.
connecting the lagoon to the sea, and correspond to lower dissolved oxygen concentrations (6.50-6.70 mg.L⁻¹). However, the 2 other poor stations correspond, for the 1st (B2), to the highest nitrate concentration (399.2 µg.L⁻¹) and, for the 2nd (B5), to the 2nd higher phosphate concentration (18.0 mg.L⁻¹). If the dissolved oxygen concentrations at B10 and B11 are very low compared to other Mediterranean lagoons, the N-P contents do not reach critical values (Mistri et al., 2000). Nevertheless, in summer, anoxic conditions can easily happen in Mediterranean eutrophic lagoons (Rossi et al., 2006).

On the other hand, the analysis of the trophic structure shows remarkable differences between sampled stations. SF co-dominates with SDF facing the principal wadis, essentially Halima/Soula (B1), Guenine/Ben Hassine (B4) and Garek (B5). The current weakness, which allows organic matter of continental origin to decant on the bottom, seems to play an important role providing food sources to these trophic groups (Kiørboe & Mohlenberg, 1981; Solis-Weiss et al., 2004). This hypothesis is confirmed by the CCA where these trophic groups are assembled together with the various forms of organic matter at the centre of the graphic. However in the top of the ship canal (B10), the codominance of SF and NSDF does not allow to discuss the potential causes because of the very low values of the density and the specific richness. But the most remarkable observation is the very strong domination of the carnivores in the majority of Bizerte lagoon stations. They are represented by several species, principally the anthozoa genus Actinia, the isopod Cymodoce truncata and the polychaetes Nephtys hombergii and Eunice pennata. In this case, an important question is raised about food resource origins ensuring the functioning of the benthic community. Studying the plankton in the same study site, Sakka Hlaili et al. (2003) note that the trophic chain in Bizerte lagoon, in the water column and also into the sediment, is of microbial type where the major participants are micro-organisms. The ultraphytoplankton (≤ 5µm), constituted mainly by small flagellates and cyano-bacterium, is the basis of this chain. These small autotrophic cells can be grazed only by microplanktonic protozoa, ciliates and large flagellates (Sanders & Wickham, 1993; Sakka et al., 2000). Then, these grazers will convey the carbon produced by the small phototrophic organisms towards the large metazoan (meiofauna and macrofauna). In Bizerte lagoon, this process is supported by the strong concentrations of the microplankton (Sakka Hlaili et al., 2003). This chain is completely different from the herbivore trophic chain in which the large cells (diatoms) dominating the ecosystem are consumed by the mesozooobenthos (Legendre & Rassoulzadegen, 1996). In general, the two types of trophic chains, microbial and herbivore, play different roles in the carbon cycle since they differently transfer biogenic carbon towards the higher trophic levels (Legendre & Rassoulzadegen, 1996). Perhaps, for this reason the distribution of trophic groups is not significantly related to the concentration of chlorophyll a in the sediment. For example, the stations exclusively dominated by the carnivores (B2, B6 and B8) record the highest values of chlorophyll a and the stations more heterogeneous on the trophic plan do not correspond necessarily to the highest concentrations of chlorophyll a. In Cretan Sea (NE Mediterranean), for example, Danovaro et al. (2000) registered relatively low concentrations of Chl.a (0.02-0.12 µg.L⁻¹) compared to our results. However, the fauna was clearly more enriched/diversified. Nevertheless, the CCA relying trophic groups and physico-chemical parameters gave a partial response at this question since the majority of the trophic groups are grouped with the main parameters having a direct or indirect relation with their trophic sources. Thus, µG are dependent on the N-P nutrients, necessary to the primary production on which they feed. The DF, NSDF and N are grouped with the various forms of organic matter which constitute their exclusive trophic sources. However, main heavy metals are grouped only with C and SDF. In fact, these trophic groups are constituted of mobile species which are generally less affected by metals than sedentary species. But it is clear that rely only on instantaneous values of the physico-chemical parameters may not reflect reality, because it is enough that certain climatic factors are strongly fluctuating at any moment of the year, so that the community changes completely to adapt its structure to the new conditions (Marchini et al., 2004).

Environmental/anthropogenic conditions

Taking into account the fine granulometry and also the strong correlations between contaminants concentrations and the sediment fine fraction content (Quevauviller et al., 1989; Caeiro et al., 2005), sediments in Bizerte lagoon seem to be capable to accumulate contaminants. However, recorded values are overall medium, except at B3 facing metallurgic factory of Menzel Bourguiba where loads of Fe, Cu, Pb, Zn and Mn are clearly higher and also in the ship canal (B10) and the harbour area facing Menzel Bourguiba (B3) where hydrocarbons loads are more important. This is probably due to the sewage of boats coming from Mediterranean sea to the port of Menzel Bourguiba.

Values of salinity and pH are also medium and do not differ clearly in the sampled stations. However the dissolved oxygen attains high concentrations, essentially at B6 and B7 far from the navigation effects, and currently Bizerte lagoon does not run hypoxia/eutrophication conditions according to Rosenberg et al. (1991). Concentrations of nutrients (nitrites, nitrates and
phosphates) are in general high, essentially at B1, B2 and B9. But in such Mediterranean lagoonal complex, environmental parameters are strongly fluctuating during the year in relation with precipitations, temperature and currents (Afli et al., 2009). In comparison with other works, Bigot et al. (2006) studying the spatio-temporal changes in the main sediment characteristics showed that contents of the total organic matter (0.60-4.10%) and the total organic carbon (0.01-1.03%) which are clearly lower than those registered in this study (respectively 2.78-29.19% and 0.08-1.19%) have a real role in the community structure. Other works in Mediterranean showed that concentrations of nutrients, organic matter and heavy metals lower than or comparable with those registered in this study had an important effect on the benthic community (Mistri et al., 2000; Ponti & Abbiati, 2004; Magni et al., 2005; Gambi & Danovaro, 2006). On the other hand, Borja et al. (2008) noted that high contents of total organic carbon and low dissolved oxygen concentrations are usually associated with most degraded sites, especially in high salinity/temperature conditions. In this case, the community richness/diversity are low, and only tolerant/opportunistic species can survive in such conditions.

Biotic indices/ecological status

Overall, Bizerte lagoon seems to be in an apparent satisfactory status since the used biotic indices (I2EC, AMBI and BENTIX) show no notable effects on the benthic macroinvertebrates, except some transitional situations distinguished by I2EC. It is the case of the marine area facing Bizerte town (B11), despite its situation at open sea, where the polychaete *Nephtys hombergii* (180 ind.m⁻²) dominates the community and the genus *Heterocirrus* is poorly present. It is also the case of the areas facing Menzel Jemil (B7) and Menzel Abderrahman (B8) and the mouth of Tinja wadi (B2) because notably of the presence of the polychaetes *Eunice pennata*, *Nematonereis unicornis* Schmarda, 1861, *Glycera convoluta* Keferstein, 1862 and *Nereis diversicolor*. However, *H*’ seems to be more severe, it shows poor statuses at the lagoon entrance (B1), in the ship canal (B10) and in the marine area facing Bizerte town (B11) and moderate statuses surrounding Menzel Bourguiba where the iron/steel plant was established. The comparison of the ecological statuses defined by the used biotic indices at the sampled stations shows that AMBI and BENTIX are the most consistent indices because 10 of the 11 stations are similarly classified by these indices (high status). However, *H*’ is completely different and does not have consistency with the other indices. Indeed, it seems to be according to Salas et al. (2004) much more influenced by specific dominances that are related to the availability of food resources and the particle size of the sediment, than by any type of disturbance. The apparent satisfactory status evaluated by the used biotic indices (I2EC, AMBI and BENTIX) can be confusing, for several reasons. Firstly, these biotic indices are initially based on the same ecological model of sensitivity/tolerance of species to increasing organic matter and habitat characteristics (Zenetos et al., 2004; Borja, 2005; Dauvin, 2007; Munari & Mistri, 2008), and not to the other stressors such as physical disturbance and chemical pollution (Borja & Muxica, 2005; Labrune et al., 2006; Borja et al., 2008). Secondly, heavy metals which are not related to these biotic indices (Carvalho et al., 2006) represent an important source of pollution in the study site because of the iron/steel plant established on its circumference. Thirdly, the real question raised here does not concern the presence of sensitive species in such polluted site, because their abundance is relatively low. But the real question is why the opportunistic species do not develop in the areas which seem favourable to their presence. It seems that other environmental constraints, like extreme temperature/salinity and the availability of food resources, play here an important role.

In conclusion, Bizerte lagoon is currently in front of many environmental/anthropogenic variables related to surrounding pollution sources and its very particular position into the lagoonal complex. Apart the pollution induced by organic matter and heavy metals, it is influenced, at the same time, by seawaters coming from the ship canal and also by freshwaters coming from Ichkeul Lake and from a large catchment’s area. Consequently, additional factors seem significantly reducing the biodiversity of the benthic macrofauna (Desroy et al., 2003), the extreme salinity and temperature, the fluctuation of nutrient supply of continental origins and the slowness of the renewal of lagoon waters. If the used biotic indices based on ecological groups seem exempting any role of pollution in the current organization of the benthic community in Bizerte lagoon, the study of the trophic structure responds, even partially, to this question. Thus, it is clear that Bizerte lagoon is currently subject to many environmental/anthropogenic stressors which have, together, an effect on the benthic community structure, and the low densities and specific richness of the benthic community are a form of response to stressors. Also, it seems that only few carnivores and, perhaps, selective deposit feeders can survive in the areas most polluted by heavy metals. In addition to the pollution and the availability of food sources, the extreme temperature and salinity between winter and summer should not be neglected, and the strong presence of euryhalin and eury-thermal species, such as *Actinia sp.*, *Cymodoce trunca*, *Dosinia lupinus* and *Tellina tenuis* (Dridi et al., 1998), confirms this hypothesis. In fact, these species are classified in the EG₁ on the basis of their sensitivity/tolerance to only organic matter and no to heavy metals.
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